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# THE PETROLEUM RESOURCES OF THE UNITED STATES.

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## INTRODUCTION.

In 1908 when the agitation for the conservation of our mineral and other natural resources was at its height, a paper was prepared by Dr. David T. Day on "The Petroleum Resources of the United States."[1] It was the privilege of the writer to contribute some of the data upon which Doctor Day based his conclusions. Since the preparation of that article much development work has been done in this country, new fields have been opened up, and the possibilities of the older fields have been more closely studied. The present paper is intended as a revision of Doctor Day's thesis in view of the latest information pertaining to the subject. The writer wishes to acknowledge his indebtedness to the following, among others, who have contributed data used in the preparation of these estimates: Jas. H. Gardner, M. J. Munn, Prof. L. C. Glenn, Prof. G. D. Harris, and Richard R. Hice.

## EXTENT OF THE PETROLEUM FIELDS.

The oil fields of the United States usually are classified as the Appalachian, Lima-Indiana, Illinois, Mid-Continent, Gulf, Rocky Mountain, California, and Alaska.

[1] Bull. U. S. Geol. Survey, No. 394, pp. 30–50, 1909.

*Appalachian Field.*—The Appalachian field extends from southwestern New York, through western Pennsylvania, southeastern Ohio, West Virginia, and eastern Kentucky, into northern Tennessee. The formations yielding the oil throughout this field include those of the Devonian and Carboniferous. The oil occurs along the axes and on the flanks of anticlines, parallel in general with the strike of the Appalachian Mountains, and on minor terraces or other structures associated with them. Occasionally it has been found in waterless synclines. The reservoir rocks are principally sandstones and coarse sediments. The oil from this field is of the best quality in the world, yielding a high percentage of the lighter oils such as gasoline and kerosene, and is utilized entirely for refining. It is of paraffin base and varies in gravity from 25° to 50° Beaumé (0.9032 to 0.7778 sp. gr.), the heavier grades coming only from the southern end of the field. The price of the "Pennsylvania grade" oil is always high, ranging up to $2.50 per barrel. The average daily production of the wells is low, being 0.2 to 0.4 barrels in 1911. This field is almost completely developed except the portions in Kentucky and Tennessee, and even here recent prospecting has resulted negatively in a majority of cases.

*Lima-Indiana Field.*—The Lima-Indiana field covers a considerable portion of northwestern Ohio and eastern Indiana. The oil is derived from the Ordovician, Silurian, and Carboniferous, largely from the Trenton limestone, the reservoir rock being porous dolomitic lenses or beds or sandstones. Favorable structures, such as half domes, terraces, etc., on the flanks of the Cincinnati uplift, usually harbor the commercial deposits. The oil is of paraffin base, varies in gravity from 30° to 35° Beaumé (0.8750 to 0.8484 sp. gr.), carries a little sulphur, and is utilized entirely for refining purposes. The average initial daily production of the wells up to 1911 was 15.5 barrels; the average daily production per well was 0.7 barrels for that year. This field also is practically outlined, although new pools are even yet being occasionally discovered.

*Illinois Field.*—The Illinois field occupies a strip of territory along the La Salle anticline in the southeastern part of the state.

It also extends a short distance into Indiana. The oil is derived largely from the Pennsylvanian and a little from the upper Mississippian (both Carboniferous), and occurs principally in well-defined sandstone horizons along the crest of the asymmetric La Salle anticline. Impregnation is governed locally by the lithology. A little of the oil comes from limestone. The oil is of paraffin base, although locally carrying some asphalt, ranges in gravity from 28° to 39° Beaumé (0.8860 to 0.8284 sp. gr.), and is used principally for refining purposes. The average initial daily production up to 1911 was 63 barrels; the average daily production of the individual wells for the same year was 4.2 barrels. With the exception of some possible territory in the western part of the state the Illinois productive area is well defined at the present time.

*Mid-Continent Field.*—The Mid-Continent field comprises the pools in Oklahoma, southeastern Kansas, and northern Texas. The oil is secured from the sandstones of the Pennsylvanian (Carboniferous) formations in domes, half domes or terraces, and local anticlines on the flanks of the great Ozark uplift. The oil is of paraffin base, varying in gravity from 27° to 41° Beaumé (0.8917 to 0.8187 sp. gr.), and is used for refining. It is piped to the Gulf and also to Indiana and other eastern states. The development in this field has been phenomenal during the past few years, some of the pools being exceedingly productive. The average initial daily production of the wells in 1911 was 119 barrels; the average daily production 8.6 barrels. A fair percentage of the region embraced in this field yet remains to be prospected, the bulk of the untested land lying in Texas.

*Gulf Field.*—The Gulf field includes the pools lying along the Coastal Plain of Louisiana and Texas. The oil occurs for the most part in domes or quaquaversals associated with salt and gypsum deposits. The age of the containing rocks ranges from Cretaceous to Quaternary. The reservoir rock is usually porous dolomitic limestone or sandstone. The oil of northern Louisiana occurs in Cretaceous and Eocene rocks along an uplift or fold. The oils of the Gulf field vary greatly in composition; those in the strictly coastal belt vary from 15° to 27.7° Beaumé (0.9655 to

0.8878 sp. gr.) and are of asphalt base; those of northern Louisiana vary from 25° to 43.6° Beaumé (0.9031 to 0.8065 sp. gr.) and are of paraffin base. Sulphur usually accompanies the heavy oil. The lighter oils are used for refining, the heavier for fuel. Some of the individual wells have been exceedingly productive, a daily flow of 75,000 barrels being recorded for one at least. The pools usually are quite short-lived. In 1911 the average initial daily flow for the Gulf coastal pools was 257 barrels; for northern Louisiana, 1176 barrels; the daily average for the field 60 barrels. Some territory still remains untested in this field.

*Rocky Mountain Field.*—The Rocky Mountain field embraces pools in Wyoming and Colorado, and as yet untested deposits in Utah and New Mexico. The oil occurs in beds of Carboniferous, Triassic (?) and Cretaceous age, nearly always in sandstone interbedded with shale, though occasionally in fracture zones. Typical dome structure is the most favorable location, but occasionally commercial deposits occupy monoclines or interrupted monoclines. The oils from the older formations vary in gravity from 18° to 24° Beaumé (0.9459 to 0.9091 sp. gr.), are of asphalt base, and are used largely for fuel; those from the Cretaceous vary from 32° to 48° Beaumé (0.8642 to 0.7865 sp. gr.), are of paraffin base, and are refined, yielding high percentages of gasoline, kerosene, and distillates. The productivity of individual wells usually is not large, the average daily yield per well being about 25 barrels in 1913. The potentialities of the Rocky Mountain field are not great unless the extensive deposits of oil shale of northwestern Colorado and northeastern Utah are taken into account. As these deposits will require a distillation process for the recovery of their oil contents, they are not included under the head of free oil deposits.

*California Field.*—California is the greatest producer of petroleum of any state in the Union. It secures its oil from rocks of Cretaceous to late Tertiary age, the great bulk coming from the Miocene. Nearly every type of structure peculiar to the Coast Ranges yields commercial quantities of oil; anticlines, domes, plunging anticlines, monoclines, and fault zones being the prin-

cipal sources. The reservoir rocks usually are sand and sandstone, though fracture joints in shale hold oil in at least one district. The oil is practically all of asphalt base, although paraffin up to 4 per cent. is found in a little of the oil from the Cretaceous and Eocene. The oil varies in gravity from 12° to 35° Beaumé (0.9859 to 0.8484 sp. gr.), about 70 per cent. of it being topped or refined. Much of the heavy oil is used for fuel and road dressing. The productivity of individual wells has reached as high as 58,000 barrels daily; the average daily production per well was 45.2 barrels in 1913. The oil districts of California are practically outlined today and little in the way of additional acreage is to be expected in the future.

*Alaska Field.*—Small quantities of oil have been obtained from the Jurassic rocks of western Alaska and the lower Tertiary of eastern Alaska. The oil occurs in sandstone along well-defined and sometimes faulted anticlines. The oil varies in gravity from 39° to 45.9° Beaumé (0.8284 to 0.7958 sp. gr.) and is of an excellent refining grade. The wells so far drilled are small producers. The commercial productivity of the Alaskan deposits yet remains to be proven.

*Other Fields.*—In addition to the states mentioned as occupying the above fields, oil occurs in small quantities in Michigan (a continuation of the Petroleo, Canada, field) and Missouri (a continuation of the Oklahoma conditions). These states and Alaska together produced but 7,792 barrels in 1914. Alabama and Mississippi also are said to have possibilities.

## IMPORTANCE OF THE UNITED STATES AS COMPARED WITH OTHER COUNTRIES.

The following table, compiled under the supervision of J. D. Northrop of the U. S. Geological Survey,[2] giving the production of crude petroleum in 1914 and from 1857 to 1914, in barrels, illustrates the relative importance of the various oil-producing countries of the world.

[2] *Mining and Scientific Press,* August 14, 1915, p. 248.

TABLE I.

WORLD'S PRODUCTION OF CRUDE PETROLEUM IN 1914 AND 1857 TO 1914, WITH PERCENTAGE OF PRODUCTION BY COUNTRIES, IN BARRELS OF 42 GALLONS.

| | 1914. | | 1857–1914. | |
|---|---|---|---|---|
| Country. | Production. | Per Cent. | Production. | Per Cent. |
| United States ..... | 265,762,535 | 66.36 | 3,335,457,140 | 59.63 |
| Russia ..... | 67,020,522 | 16.74 | 1,622,233,845 | 29.00 |
| Mexico ..... | 21,188,427 | 5.29 | 90,359,869 | 1.62 |
| Roumania ..... | 12,826,579 | 3.20 | 117,982,474 | 2.11 |
| Dutch East Indies ... | 12,705,208[1] | 3.17 | 138,278,392 | 2.47 |
| India ..... | 8,000,000[2] | 2.00 | 73,979,919 | 1.32 |
| Galicia ..... | 5,033,350[2] | 1.26 | 131,873,601 | 2.36 |
| Japan ..... | 2,738,378[3] | .68 | 27,051,158 | .48 |
| Peru ..... | 1,917,802 | .48 | 14,306,972 | .26 |
| Germany ..... | 995,764[2] | .25 | 12,965,569 | .23 |
| Egypt ..... | 777,038 | .19 | 1,086,728 | .02 |
| Trinidad ..... | 643,533 | .16 | 2,069,430 | .04 |
| Canada ..... | 214,805 | .05 | 23,493,610 | .42 |
| Italy ..... | 39,548 | .01 | 802,229 | .01 |
| Other countries ..... | 620,000[4] | .16 | 1,322,000 | .03 |
| | 400,483,489 | 100.00 | 5,593,262,936 | 100.00 |

[1] Includes British Borneo.
[2] Estimated.
[3] Includes Formosa.
[4] Includes 600,000 barrels produced in Argentina.

The relative importance of the states in the Union is shown in the table on the following page, which gives the marketed production for the year 1914. In the case of two of the states, at least, the marketed production is below the estimated production, the discrepancy being accounted for by oil put in storage. The actual production of California was probably around 103,000,000 barrels, with possibly 7,000,000 barrels "shut in," which might have been produced. The estimated production of Oklahoma was 98,000,000 barrels.

### FACTORS GOVERNING THE PRODUCTION OF PETROLEUM.

Before entering into a discussion of the probable future production of petroleum in the United States, it will be well to outline the various factors which govern this production. These factors may be divided into two groups, natural and artificial.

TABLE II.

PRODUCTION OF PETROLEUM IN THE UNITED STATES, BY STATES, IN 1914 AND 1857 TO 1914, IN BARRELS OF 42 GALLONS.

| | 1914. | 1857–1914. |
|---|---|---|
| Alaska | (*a*) | |
| California | 99,775,327 | 741,273,559 |
| Colorado | 222,773 | 10,649,143 |
| Illinois | 21,919,749 | 232,326,616 |
| Indiana | 1,335,456 | 102,823,798 |
| Kansas | 3,103,585 | 28,547,074 |
| Kentucky | 502,441 | 9,095,970 |
| Louisiana | 14,309,435 | 89,895,433 |
| Michigan | (*a*) | 72,712 |
| Missouri | (*a*) | |
| New Mexico | —— | |
| New York | 938,974 | (*b*) |
| Ohio | 8,536,352 | 432,762,004 |
| Oklahoma | 73,631,724 | 461,833,466 |
| Pennsylvania | 8,170,335 | 754,180,215 |
| Texas | 20,068,184 | 203,799,381 |
| West Virginia | 9,680,033 | 260,232,815 |
| Wyoming | 3,560,375 | 7,964,944 |
| Other | 7,792 | |
| | 265,762,535 | 3,335,457,130 |

*a*—Included in "Other."
*b*—Included in Pennsylvania.

### *A. Natural Factors.*

1. *Pressure.*—The pressure exerted on the oil in its underground reservoir may be hydrostatic, hydraulic, or gas; it may be co-extensive with the field or pool, in which case it is called "field pressure," or it may be exceedingly local in extent, when it is called "local" or "well pressure." Pressure in oil wells varies from 0 to over 2,000 lbs. per square inch, usually declining as the field or well grows old. Other things being equal, the production varies with the pressure.

2. *Viscosity.*—Production varies inversely with the viscosity, and since the viscosity in general increases with the specific gravity (increases inversely with the Beaumé degrees) it may be said that, other conditions being equal, the production varies inversely with the specific gravity of the oil. Natural petroleums vary from

substances as fluid as water (low viscosity) to those having the consistency of "cold molasses" (high viscosity), or even to those possessing the properties of solids.

3. *Thickness and Extent of Reservoir Rocks.*—The production varies with the thickness and extent of the reservoir rock. The thickness of the pay streaks may vary from 2 feet, as in some fields of the eastern United States, to over 200 feet, as in some California fields. The lateral extent of the layer or lens may be from a few feet to several miles.

4. *Porosity of Reservoir Rock.*—Production varies inversely with the porosity within certain limits. In uniformly grained rocks the coarser the grain of the reservoir the less is the actual porosity; but the larger the size of the interstices the less is the friction surface per unit of oil. Therefore, coarse sediments are really less porous and consequently hold less oil, but they give it up more readily than fine sediments and usually give a greater ultimate yield per unit of volume. Reservoir rocks may be fine shale to the coarsest conglomerates, or porous or cavernous dolomites or limestones. Fracture or fault zones also may act as reservoirs. The world's maximum producers obtain their oil from cavernous limestones or dolomites; the steadiest and longest-lived wells are in medium-grained sand.

5. *Structure of Reservoir Rocks.*—Structure usually has a profound influence on oil accumulation and production, the most advantageous positions being in the crests of domes or anticlines, or on the flanks of sealed or terraced monoclines. Lithology or other causes may locally produce exceptions to all rules of accumulation.

### *B. Artificial Factors.*

1. *Price of Oil.*—The price of oil is the dominant factor governing the production of oil, especially as it relates to groups of wells, fields, districts, or states. The price may vary from 10 to 15 cents a barrel at the well, as at certain periods in the history of the Mexican or California fields, or it may range up to $2.50 per barrel, and in exceptional cases much higher, when the demand

is great and the supply limited. Price of oil largely affects the other artificial factors, which may be summarized as follows:

2. *Depth of Wells and Time Required to Drill.*—Production may be accelerated or retarded by the time required to drill wells. In some places wells can be put down in a week or ten days; elsewhere it may take from 1 to 2 years to finish a well. In a shallow well district production can be increased quickly by a vigorous drilling program; in deep well areas much time and money may be necessary to increase or even sustain production.

3. *Distance Separating Wells.*—Within a certain underground reservoir, the quantity of oil that ultimately can be recovered and the rapidity with which it may be produced are largely dependent on the distance separating the individual wells. The thicker the wells the quicker the recovery of the oil and the greater the expense of recovery. Wells may be spaced 25 feet apart or as near together as the derricks will stand, as in the congested Spindletop field of Texas, or they may be separated by a distance of ¼ mile or more. Ownership of property often determines the spacing of the wells, many small tracts under separate ownership tending toward congestion of development and rapidity of recovery. Conservation is best attained by single ownership of large bodies of land, so that development will be determined by the principle of recovering the oil at the least possible expense, that is, with the least number of wells.

4. *Condition of Well, Pump, etc.*—The condition of the well, pump, and other physical properties involved in the winning of the oil greatly influences the production. Clean wells, efficient pumps, and energetic employees tend toward maximum production; sanded up or improperly perforated wells, leaky pumps, and inexperienced or careless employees militate against successful operation.

5. *Discovery of New Fields.*—The discovery of new fields is a most potent factor in oil production. The search for new fields is stimulated by high prices; their discovery usually results in a flush yield and a lowering of the price. Obviously, each new field raises the normal production to be expected from any dis-

trict or state, and it is this factor of new territory which lends so much uncertainty to the oil business.

6. *Distance from Market.*—The distance from market of any field or group of wells often determines the rate of development and consequent production. Those fields nearest to market or favorable transportation facilities are usually quickly developed to their maximum capacity, while fields further away are often left for years without even being adequately prospected.

7. *Improvements in Development and Recovery Methods.*—New methods of drilling and increasingly efficient methods of recovery are favorably affecting production in many fields. The most important advance in recent years has been along the line of increased use of compressed air in the recovery of oil, especially in California and Pennsylvania.

8. *Water Complications.*—"Water troubles" may be either natural or a combination of natural conditions and human carelessness or ignorance. Water causes the final ruin of practically all oil fields; it is the omnipresent and greatest menace of the producing fields. In most cases water troubles are inexcusable. Their results almost always are negative and sometimes irremediable.

Oil in most fields of the United States and, in fact, throughout the world, occurs in inclined or sloping beds of sand or other porous rock, and these oil zones usually are overlain and underlain by water sands or zones which are separated from the oil zones by impervious clay, shale, or other strata. In these two cases the water is extraneous to the oil sands. These waters are called "top" and "bottom" waters, in accordance with their occurrence, respectively, above or below the oil zones. In a properly finished well the "top" water is cased off or cemented off before the well is drilled into the oil sand. The "bottom" water never is drilled into except by accident, in which event it is plugged off. With the "top" water shut off and the "bottom" water untouched, the oil is produced practically free from water. Water, being heavier than oil and often also under a greater hydrostatic pressure, will replace part or all of the oil at the point of ingress into the well if it is allowed to reach the oil sand. In

this way it replaces the oil, in whole or in part, and thus lessens the amount of oil produced and increases its cost of recovery. Water also occurs indigenous to the oil sands in certain fields, but in this case it does not at first occupy the same part of the stratum as that occupied by the oil, but lies in the lower or "down-slope" portion of the sand, and the line marking the junction of the oil in the "up-slope" part of the bed and the water in the "down-slope" part determines the limits of the productive territory. The water under these conditions is called "edge" water. Upon exhaustion of the oil by flowing or pumping, the "edge" water, through hydrostatic or other pressure, usually "follows up" and replaces the oil. The appearance of the originally extraneous "top" water or "bottom" water in a well indicates a failure to exclude the water properly by the manipulation of casing, cement, or plugs. Such a condition usually can be remedied and the offending fluid kept out of the oil sand, although what has come in already may sometimes remain in the oil to a greater or lesser extent. The appearance of "edge" water in a well is another matter, for here the oil has been permanently replaced by the water, and, so far as the affected sand is concerned, the well can be considered as no longer productive. "Edge" water sometimes appears in a well in some particular sand, while other producing sands are free from water. In this instance, the "edge" water sand is abandoned and cased off and the production continued from the other sands.

Most of the water troubles are due to a failure to shut off the "top" water in the process of drilling. Wells, properties, and entire fields have been seriously damaged or entirely ruined by the water, sometimes from only a few offending wells. This factor of water is, therefore, one of the most potent in oil production and at the same time the most uncertain.

### METHODS OF ESTIMATING FUTURE SUPPLY.

Two methods of estimating the future production or supply of oil in any area or field are in use, one known as the saturation method, the other, the production curve method.

*Saturation Method.*[3]

The saturation method of computation involves finding the cubical contents of the reservoir, determining the degree of porosity of the volume, and then estimating the total, available, and net supply of oil contained under the area in question. By total supply is meant the total quantity of oil in the reservoir; by available supply is meant the quantity that theoretically can be recovered with ordinary methods in vogue; net supply is the quantity marketed after deducting for fuel used in development and operation, leakage, and other losses.

Total supply depends on the volume and porosity of the reservoir and on the volume of free gas and of water which are included in the oil. The first factor usually can be approximated by taking the area involved and multiplying by the average thickness of the oil sand or zone. The porosity can be approximated from outcrop samples or drilling samples of the reservoir. Gas and water contents are uncertain, but in most instances can be disregarded for rough approximations. Gas usually is in solution and the water only in the outlying edges of the oil pools. Available saturation may range from 0 to, possibly, 80 per cent., depending largely on the gas pressure and other factors, such as grain of reservoir, coherency, etc. From 40 to 60 per cent. of the total quantity ordinarily is recoverable. Of this quantity possibly 10 per cent. to 15 per cent. is lost in production or used for fuel, so that of the total supply but 34 per cent. to 54 per cent. ordinarily is marketed. Many years may be required to make even this recovery.

It is the writer's belief that estimates based on the saturation method are much less reliable and satisfactory than those worked out through the production curve method, but the former must be used for new or poorly developed fields and will be briefly described.

The thickness of producing oil sands or oil zones varies from 2 feet in the Illinois field to over 200 feet in the California field. Total supply or saturation as marked by the porosity varies from

[3] This method is described by Chester W. Washburne, *Bull. A. I. M. E.*, No. 98, February, 1915, pp. 469–471.

a trace, in sands, up to 50 per cent. in some exceedingly porous diatomaceous shale from California. Between 5 and 15 per cent. is the average for sands, some, however, going as high as 30 per cent. An acre of ground covered with oil a foot deep (1 acre-foot) contains 7,758 barrels. This would be complete saturation for the 43,560 cubic feet. Assuming an average of 10 per cent. saturation would give 775.8 barrels per acre-foot for normal conditions. On this basis a 5-foot sand would contain 3,879 barrels per acre, and a 50-foot sand 38,790 barrels. Actual yields of over 100,000 barrels per acre are known. Estimates of the average production per acre for the various states are given in Table III. on page 710. Most of these figures are based primarily on the production curve method, but a few are based on or checked by the saturation method.

### *Production Curve Method.*

*General Statement.*—Estimating future production or supply by a plotting of hypothetical curves, based on actual figures in well-known areas or fields, is the safest method as it involves factors which it is possible to obtain. Another thing in its favor from the standpoint of the producer and marketer of oil is that it is based on and has to do with actual "net" oil figures, instead of theoretical quantities.

*Basis of Theoretical Curve.*—The theoretical curve shown in the diagram accompanying this article is based primarily on the yearly total production figures of New York and Pennsylvania. These figures cover a period of productivity of 54 years, longer by far than that of any other field in the United States. Furthermore, over this period this field has been subject to all of the vicissitudes from both natural and artificial causes that beset oil fields in general. The area involved in the Pennsylvania and New York field is greater than that in any other field in the United States, which is still another reason why the result should be conservative.

The interesting part of the production curve is that following the period of maximum yield. In some instances it is fairly safe

Curves of Production of Principal States and Theoretical Curve of Final Decrease
— Legend —
California
Illinois
Texas
Louisiana
Oklahoma
Penna & N.Y.
Ohio
West Virginia
Indiana
Theoretical Final Decrease
Millions of Barrels

to predict just when this period is reached, although usually a great divergence of opinion prevails, due to whether the prophet is a producer or a consumer. As a rule, the crest of the production curve is not a sharp peak, but is represented by a more or less wavy dome, showing that the production remains near the maximum for several years. In the case of the Pennsylvania-New York curve, the period of high production extended over about ten years; that of Ohio and West Virginia over eight years; and that of Illinois over two years. Following this period the production is more or less irregular, but in general decreases at a fairly regular rate, the rate of decrease, based on the previous year's production, becoming gradually less and less as is indicated in the theoretical curve in the diagram. In figures this decrease may be tabulated thus, the basis of computation being the maximum yearly production for the field:'

| | |
|---|---|
| At end 1st 10 years, 50 % max. prod. | Average for 10 years, 75 % max. prod. |
| At end 2d 10 years, 30 % max. prod. | Average for 10 years, 40 % max. prod. |
| At end 3d 10 years, 20 % max. prod. | Average for 10 years, 25 % max. prod. |
| At end 4th 10 years, 15 % max. prod. | Average for 10 years, 17.5 % max. prod. |
| At end 5th 10 years, 12.5% max. prod. | Average for 10 years, 13.75% max. prod. |
| At end 6th 10 years, 10 % max. prod. | Average for 10 years, 11.25% max. prod. |

The usual development history in the period of high production is, first, a decrease of yield, followed by increase in price, then renewed development activity with a resultant increase in yield, a fall in price, and so on until the development reaches a point where the production of new wells fails to make up the decrease of the old, when the final period of decrease begins.

### ESTIMATED FUTURE PRODUCTION.

The following table gives the estimated future production of petroleum in the United States, together with the approximate figures as to the proven and prospective oil-bearing areas, and a summary of the principal points regarding the occurrence and character of the oil.

The figures of future supply take into account a certain per

TABLE III.

PAST AND ESTIMATED FUTURE PRODUCTION OF PETROLEUM IN THE UNITED STATES.

| State. | Age of Containing Rocks. | Base. | Quality of Oil. | Production for 1914. | Total Prod., Including 1914. | Probable Future Supply. | Proven Area. | Prospective Area. | Average Prod. per Acre. | Per Cent. Exhaustion. |
|---|---|---|---|---|---|---|---|---|---|---|
| Alaska..... | East-Low. Tertiary<br>West-Jurassic | Paraffin | 39°–45.9° B.<br>0.8284–0.7958 | —— | —— | 10,000,000 | — | 15 | 1,000 | 0 |
| California... | Cretaceous; Tertiary | Asphalt | 12°–35° B.<br>0.9859–0.8484 | 99,775,327 | 741,273,559 | 2,300,000,000 | 156 | 40 | 30,000 | 24 |
| Colorado.... | Pierre-Cretaceous | Paraffin | 38°–44° B.<br>0.8333–0.8045 | 222,773 | 10,649,143 | 21,000,000 | 17 | 33 | 1,000 | 33½ |
| Illinois..... | Mississippian-Penna. | Paraffin | 28°–39° B.<br>0.8860–0.8284 | 21,919,749 | 232,326,616 | 400,000,000 | 400 | 100 | 2,500 | 36+ |
| Indiana..... | East-Ordovician(Trenton)<br>West-Pennsylvanian | Paraffin | 30°–35° B.<br>0.8750–0.8484 | 1,335,456 | 102,823,798 | 20,000,000 | 500 | 100 | 400 | 83+ |
| Kansas..... | Pennsylvanian | Par.-Asph. | 27°–38° B.<br>0.8917–0.8333 | 3,103,585 | 28,547,074 | 40,000,000 | 70 | 30 | 1,500 | 42 |
| Kentucky, Tennessee | Mississippian | Paraffin | 25°–43° B.<br>0.9032–0.8092 | 502,441 | 9,095,970 | 10,000,000 | 100 | 100 | 300 | 47 |
| Louisiana.... | Cretaceous-Quat.<br>Cretaceous-Eocene | Paraffin | 21°–41° B.<br>0.9271–0.8187 | 14,309,435 | 89,895,433 | 170,000,000 | 87 | 40 | 4,500 | 34 |
| Michigan, Missouri | Carboniferous | Paraffin | 30° B.<br>0.8750 | 7,792 | 72,712 | 100,000 | 1 | — | — | 58 |
| New Mexico. | Carboniferous-Cretaceous | | | | | | | 25 | | |
| New York and Penna. | Devonian-Carboniferous | Paraffin | 25°–50° B.<br>0.9032–0.7778 | 9,109,309 | 754,180,215 | 135,000,000 | 1400 | 100 | 1,000 | 85 |
| Ohio—East and West | Ordovician-Carboniferous | Paraffin | 35°–47° B.<br>0.8484–0.7909 | 8,536,352 | 432,762,004 | 205,000,000 | 115<br>535 | —<br>50 | 1,500 | 67 |
| Oklahoma... | Pennsylvanian | Paraffin | 32°–41° B.<br>0.8641–0.8187 | 73,631,724 | 461,833,466 | 1,545,000,000 | 297 | 73 | 10,000 | 22 |
| Texas..... | Pennsylvanian, Cretaceous-Quat. | Asphalt and Paraffin | 15°–38° B.<br>0.9655–0.8333 | 20,068,184 | 203,799,381 | 400,000,000 | 50 | 150 | 17,000 | 33+ |
| Utah..... | | | 22°–40° B.<br>0.9210–0.8235 | | | | | 20 | | |
| West Va..... | Devonian-Carboniferous | | 27°–52° B.<br>0.8917–0.76 2 | 9,680,033 | 260,232,815 | 207,000,000 | 350 | 50 | 2,000 | 55+ |
| Wyoming.... | Carboniferous-Cretaceous | Asphalt-Paraffin | 18°–48° B.<br>0.9459–0.7865 | 3,560,375 | 7,964,944 | 300,000,000 | 31 | 20 | 15,000 | 2 |
| | | | | 265,762,535 | 3,335,457,130 | 5,763,100,000 | 4109 | 946 | | 36 |

cent of the prospective oil area, as the curve on which they are based pertains to an area where new fields have been added from time to time as development progressed. In the case of Texas, Wyoming, etc., where the ratio of prospective area to proven area is high, the future supply may be considerably greater than that predicted if the bulk of the prospective land proves productive.

*Comparison with Dr. Day's Figures for 1908.*

The following is a comparison of the estimates given by Dr. Day for 1908 with those by the writer for 1915. They are here presented by fields in order to correspond with Dr. Day's divisions.

TABLE IV.

ESTIMATED TOTAL PRODUCTION OF THE UNITED STATES BY FIELDS.

| | Arnold—1915. | | Day—1908. | |
|---|---|---|---|---|
| | Per Cent. | Total Prod. | Minimum. | Maximum. |
| Appalachian | 19 | 1,729,809,000 | 2,000,000,000 | 5,000,000,000 |
| Lima-Indiana | 04 | 406,286,000 | 1,000,000,000 | 3,000,000,000 |
| Illinois | 07 | 632,327,000 | 350,000,000 | 1,000,000,000 |
| Mid-Continent | 26 | 2,346,000,000 | 400,000,000 | 1,000,000,000 |
| Gulf | 06 | 592,895,433 | 250,000,000 | 1,000,000,000 |
| California | 33 | 041,273,000 | 5,000,000,000 | 8,500,000,000 |
| Minor Fields | 05 | 1,349,966,707 | 1,000,000,000 | 5,000,000,000 |
| | 100 | 9,098,557,140 | 10,000,000,000 | 24,500,000,000 |

Comparing the writer's estimates with those of Dr. Day, it is at once apparent that the estimates for the older eastern fields have been reduced while those for the western fields have been increased. This is especially true for the Mid-Continent field, in which there was little development at the time Dr. Day's figures were compiled. In the case of California[4] it has been found that the available saturation is less than was expected during the early history of the field. At the time the first estimates were made the field gas pressure was high and water trouble had not become serious; with the lapse of time it has become evident that a re-

[4] Dr. Geo. Otis Smith discusses the duration of California petroleum resources in Min. Res. U. S. for 1910, Pt. II, p. 416, *et seq.*

duced gas pressure and water infiltration necessitate materially cutting the original figures.

At the present rate of consumption of approximately 265,000,000 barrels per year, an estimated supply of 5,763,100,000 barrels would last only, approximately, 22 years. However, as the total production of the United States will gradually decrease from year to year, it is believed that the total available supply will spread out over a period of from 50 to 75 years. The price of oil, which now ranges from 40 cents to $2.00 per barrel (average 95 cents), depending on the locality and grade of the product, probably will increase to figures approximating $1.00 per barrel for fuel oil and possibly $5.00 or more for the lighter grades. All other factors being equal, a barrel of fuel oil as compared with coal on the Pacific Coast is worth today 93 cents. Even were oil to be used only as a fuel, the tendency would be for it to rise in price until it reached a point set by the value of coal in the same regions. As oil has so many points in its favor, as regards ease of handling, cleanliness, etc., it is quite evident that eventually it will be sold at a higher price than is warranted by its heat value as compared with that of coal.

Before the free natural petroleum in the earth is exhausted, the oil shales of Colorado, Utah, California, and other states will have begun to be utilized as a source of petroleum. Also artificial oil made from animal and vegetable waste probably will be available to take its place. Even at the present time the necessities of war have led certain of the European governments to utilize various substitutes for petroleum and its derivatives, the substitutes in general being made from organic substances.

In conclusion, the writer might repeat what often has been pointed out by conservationists, that oil as far as possible should be used for those purposes for which we have no other substitute, namely, for lubricants, refined derivatives, etc., and not for fuel. If used for fuel, it should not be in connection with the wasteful steam engine, but in the Diesel engine and similar types which are so much more efficient that their use doubtless will become more and more general as time goes on.

Los Angeles, Cal.,
September 28, 1915.

# GEOLOGY AND ORE-DEPOSITION AT TONOPAH, NEVADA.

J. E. SPURR.

SYNOPSIS.

At Tonopah the oldest rock is a trachyte flow highly altered to quartz, sericite, and adularia. The lower part of this flow is a fine flow-banded glassy trachyte. The main body of the trachyte contains the oldest and by far the most important group of mineral veins; the glassy trachyte appears practically barren.

Stresses subsequent to the trachyte extrusion produced horizontal fissuring near the zone of transition between the main body of trachyte and its glassy lower portion; and along here an andesite (Sandgrass andesite) intrusion penetrated. After renewed fissuring along the same zone, a glassy trachy-alaskitic intrusion (Montana breccia), very full of inclusions, took place, usually following along immediately above the andesite. Subsequent movement reopened this line of weakness, and a second trachy-alaskitic intrusion came in—the West End rhyolite sheet—which penetrated along a fissure usually lying immediately above the Montana breccia. At a subsequent epoch came an eruption of andesite (Midway andesite) as a surface flow; at a still later epoch there was a series or rhyolitic and alaskitic surface flows and intrusions, of which the most important in the mine workings is a great intrusive mass called the Tonopah rhyolite.

The principal veins were formed after the trachyte eruption and before the Sandgrass andesite-Montana breccia-West End rhyolite intrusions. They are quartz veins carrying silver and gold. A second set of veins was formed after the West End rhyolite intrusion and before the Midway andesite eruption. This second set is divided into four successive groups—*A*, large typically barren quartz veins; *B*, tungsten-bearing veins; *C*, mixed

quartz and adularia veins, typically barren; *D,* productive veins like those of the first set following the trachyte. A third set of veins was formed after the Tonopah rhyolite intrusion. They are quartz veins carrying occasional lead, zinc and copper sulphides.

All these veins formed at shallow depths, and the different types are held to represent various stages of temperature. The First Period veins represent the normal shallow-seated type, and followed the trachyte eruption; the Second Period B veins probably represent an abnormally intense shortly-sustained temperature, following the trachy-alaskitic intrusion; the Second Period D veins a subsequent briefly-sustained stage of temperature more normal to shallow depths; the Third Period a relatively high but briefly-sustained temperature following the alaskitic (Tonopah rhyolite) intrusion. No vein-formation followed the andesite eruption.

The history of faulting is long and complex; important movements have taken place at every stage of the geologic history. These movements accompanied and were due to the volcanic disturbances.

## HISTORY OF GEOLOGIC INVESTIGATION AT TONOPAH.

### *Conclusions in 1902.*

When the writer made his first study of the mines of Tonopah, in the summer of 1902, he identified the highly altered and variable-appearing rock in which the principal veins were found as andesitic; and found that this rock was frequently covered by another andesite, later than the principal ore-deposition, and therefore barren of ore and forming a "cap-rock" to the ore-bearing veins. The formation which enclosed the veins he called the "earlier andesite"; the younger rock the "later andesite." Still younger than the "later andesite" he found a variety of volcanic rocks, largely extrusive surface formations including tuffs, explosive breccias, and flows, but also partly intrusive. These younger rocks were chiefly rhyolitic in composition. One of the most conspicuous of these rhyolitic rocks was a rock with a glassy groundmass, usually packed full of angular inclusions of

similar glassy rhyolite, so that the whole had usually the structure of a breccia. This rock occurred chiefly as surface flows in the district south of the town of Tonopah. To the north of the town, however, it was found to outcrop abundantly in the guise of an intrusive rock, younger than the later andesite. To this rock the name Tonopah rhyolite-dacite was given; it appeared to be plainly an autoclastic volcanic breccia. The origin seemed to be due to periods of quiescence and partial congelation in a volcanic vent, alternating with periods of upward propulsion of the viscous lava, so that the hardened glassy crusts were shattered and carried along in the upwelling still fluid portion of the same lava. These incidents repeated a number of times produced the peculiar and characteristic structure of the finally solidified rock as we find it.

Also later than the ores, and roughly contemporaneous with the Tonopah rhyolite-dacite eruptions and related intrusions (the span of the period of activity of this lava was considerable) he found a series of waterlaid tuffs formed in a lake of vast extent, and later than these tuffs, a number of volcanic necks, formed of distinct but closely related lavas of rhyolitic composition merging toward dacitic composition.

In sum, it appeared that the productive veins had formed after the eruption of the "earlier andesite" (which was and is still believed to be in large measure at least a surface flow) and before the advent of the numerous other volcanic and volcanic-detrital mentioned. The whole volcanic history including the formation of the ore-deposits was found to belong to the Tertiary, probably Miocene-Pliocene.

### NEW INFORMATION OBTAINED IN 1903.

Returning to Tonopah in the summer of 1903 for a brief examination of recent developments before the publication of his report, the writer found that a number of shafts had, after passing down through the earlier andesite, encountered, at a depth of a few hundred feet, a dense greenish glassy rock, highly altered and essentially aphanitic, but evidently of rhyolitic nature.

This rock is characterized by numerous angular light-colored or white inclusions, apparently of altered rhyolitic glass of much the same nature as the matrix, so that the whole rock appears to be an autoclastic glassy rhyolite. The most important veins seemed to be cut off by this rhyolite, whence it was concluded that the rhyolite was an intrusive sheet, younger than the "earlier andesite" and the principal ore-deposition; and this view, after recent exhaustive investigation, is still held. Since this rock was closely similar to the outcropping intrusive Tonopah rhyolite-dacite in the vicinity, it was correlated with this formation. This correlation has long since been definitely abandoned, as subsequent extensive development work has proved that this underground rhyolite is of distinctly greater age than the Tonopah rhyolite-dacite (or Tonopah rhyolite, as it may be called, with more simplicity and as much accuracy) and nowhere in the surveyed and mapped district outcrops at the surface. Thus it constitutes a new formation, unexposed at the time of the original investigation. It has been conveniently designated the "West End rhyolite."

It was observed by the writer, in the summer of 1903, that there was evidence of a second period of vein-formation, later than the West End rhyolite. The description of these later veins still holds, and will be referred to more particularly later. They are less definite and persistent than the veins of the first period, contain great quantities of low grade or barren quartz, and the pay-ore, where it does occur, is often spotty and usually, though not always, of low grade.

The developments observed in the summer of 1903 also showed that several shafts had passed through the sheet of West End rhyolite into andesite, having apparently the general composition of the "earlier andesite" above the sheet, and highly altered by hot-water action. No development work whatever had been done in this lower andesite body, but it was especially remarked that the alteration of this rock was entirely of the sort sometimes designated as "propylitic"—*i. e.*, to calcite, chlorite, and pyrite, so that the rock took on a characteristic dark-green color;

while the "earlier andesite" above the West End rhyolite sheet was more typically altered to quartz, sericite, and adularia. Evidences of propylitic alteration in the "earlier andesite" were, however, abundant in many places, so that the lower andesite was correlated with the "earlier andesite," although it was pointed out that this "calcitic phase of the earlier andesite" was not associated with the ores.[1]

At the time of this second examination in 1903 a vertical drill-hole downward from the bottom of the Mizpah shaft had encountered a rock which the writer identified as rhyolite, and correlated it with the "Tonopah rhyolite" and on this basis interpreted it as a barren formation, in which no pay-ore would be found. This correlation and interpretation have been confirmed by the writer's recent investigations. In the Mizpah Extension shaft part of probably the same underground rhyolitic body was observed in 1903, and, as it still appears, correctly correlated. This deep-seated sheet became subsequently locally known as the "Lower rhyolite."

### *Progress of Development Work and Modifications of Geological Views.*

The extensive underground development of the succeeding years emphasized the distinction between the lower andesite body, or the "calcitic phase of the earlier andesite," and the upper or original "earlier andesite" mass. The first-named rock, whose designation became usually locally abbreviated to "calcitic andesite," was found to have a considerable lateral extent, with the general form of a sheet underlying the West End rhyolite sheet, and overlying the deeper Tonopah rhyolite (usually called locally the "lower rhyolite") mass, which was also found to have considerable lateral extent. The green color due to the type of alteration of the "calcitic andesite" was found to be quite uniform, and the relative scarcity of silicification or veins in this rock became increasingly apparent.

In the summer of 1908 the writer returned to Tonopah for an

[1] Professional Paper No. 42, U. S. G. S., p. 32.

examination of the West End and MacNamara mines. At that time he determined the fact that the "West End rhyolite" sheet could not be correlated with the "Tonopah rhyolite" but was distinctly older. One of the strong arguments for the intrusive nature of the West End rhyolite sheet was therefore withdrawn, and a reviewal of the whole argument became necessary, for if the rhyolite sheet were not intrusive, the main argument for the correlation of the underlying "calcitic andesite" with the overlying original "earlier andesite" was also withdrawn. The uniform points of distinction between the two andesitic rocks, now more clearly exhibited on account of new development work, led finally to the conclusion that the two andesitic sheets were indeed distinct and independent rock-formations.

In this new light a possible explanation appeared to be that the different formations were merely a series of regularly successive flows. This explanation was considered by the writer, although it by no means explained the peculiar relations of the rocks to the mineral veins, as it still appeared that the most important veins in the "earlier andesite" were cut off by the West End rhyolite sheet.

In December 1909 the thesis that the different rock formations at Tonopah were a series of successive surface flows was brought out in a publication by Mr. J. A. Burgess, geologist for the Tonopah Mining Company.[2]

As a strong point in favor of this view mention was made of the discovery, in the Mizpah mine and in the uppermost portion of the "lower rhyolite," of white dense banded rocks having the appearance of stratified tuffs, alternating with the coarser breccia such as is more common in this formation. Further specimens were found in cores obtained by deep drilling which could be easily interpreted, on account of their definitely banded character, as stratified. Microscopic examinations made by Mr. E. S. Larsen of the Carnegie Institute showed an essentially fragmental character of these rocks, and this led to their designation as well-bedded tuffs.

[2] Economic Geology, Vol. IV., No. 8, p. 681.

*Outline of Results of Recent Study.*

In the early part of 1910 arrangements were made with the writer by the principal mining companies of Tonopah for a thorough geological investigation, to supplement his original report published by the Geological Survey, and to investigate the import of data subsequently exposed by development, with its bearing upon the future method of development work in the camp. Accordingly the writer spent a number of months in close detailed underground studies and mapping, and investigated in detail the mines of the Tonopah Mining Company, the Montana Tonopah, the Belmont, and the Midway, all adjacent and forming as a group a unit. The "earlier andesite" was still found to be the oldest of the rocks, but proved to be a trachyte instead of an andesite and was named the Mizpah trachyte. In its lower portion it passes by transition into a dense banded glassy basal phase, called by the writer the Glassy trachyte. This "Glassy trachyte" was at least several hundred feet thick, but where the exact base was, or on what older formation this flow rested, is not known, although blocks of an andesite, found engulfed in the West End rhyolite in the mines in the western portion of the camp, are now thought to perhaps represent the formation originally underlying the Glassy trachyte. Small quartz veins have been found in these andesite blocks. The West End rhyolite was determined to be an intrusive sheet, mainly inserted along the zone between the "Glassy trachyte" and the "Mizpah trachyte" proper, but showing much irregularity. The "calcitic andesite" was found to be a distinctly intrusive sheet of great irregularity. It was tentatively correlated with the "later andesite." The "lower rhyolite" was shown to be younger than the "later andesite," was correlated with the "Tonopah rhyolite" as was done at the time of the original investigation, and was found to be younger than the "calcitic andesite" sheet, which it underlies and is locally known to intrude. This "lower rhyolite" is evidently the flatly downward-pitching extension of the great mass of intrusive "Tonopah rhyolite" exposed on the surface half a mile or so to the north of the main producing mines.

A new formation was recognized and described as the "Montana breccia." This is an intrusive sheet or sill of alaskitic glass containing an immense amount of foreign inclusions, especially of the Glassy trachyte. In point of age it immediately preceded the West End rhyolite, which intrudes it.

The veins were divided into three groups according to their age, which groups correspond essentially with those originally made by the writer.

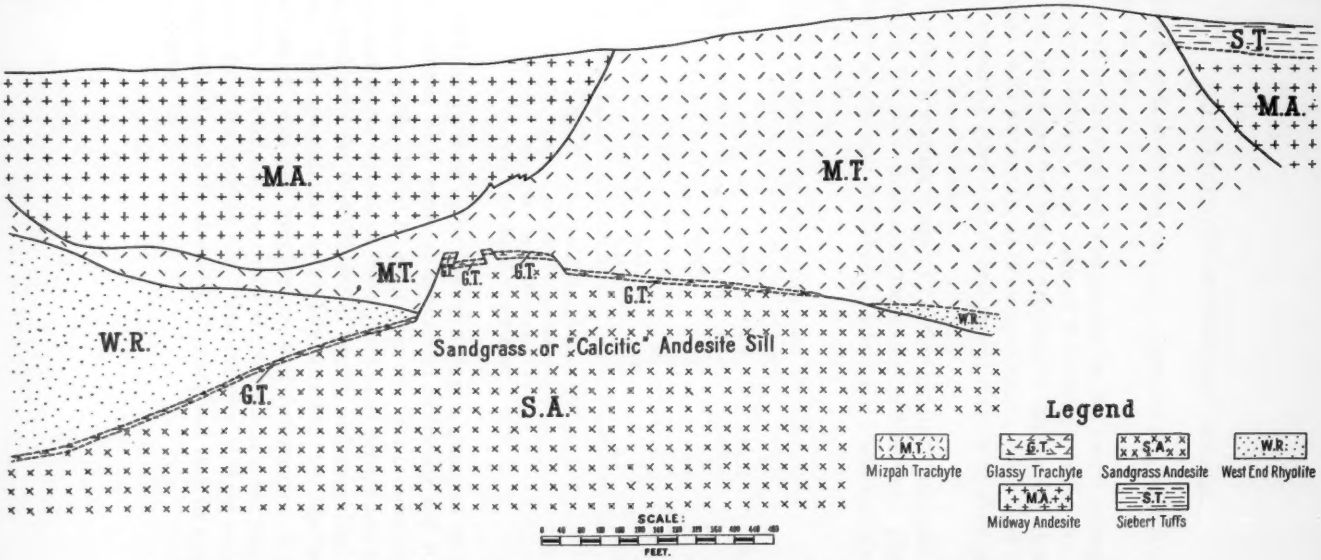
From 1912 to the present time the writer has been an official of the original Tonopah company (Tonopah Mining Company) and has maintained a geological survey of the new developments. Recent events led to his personally examining carefully and mapping the Tonopah Extension mine, together with adjacent properties.

The principal result of this recent work has been to fix definitely the position of the "calcitic andesite." Originally referred to the "earlier andesite," and afterwards to the "later andesite" it is now found to be intermediate in age between the two, is younger than the Mizpah trachyte and the Glassy trachyte and the first period vein-formation, and older than the Montana breccia and the West End rhyolite.

## THE MIZPAH TRACHYTE.

### *Chemical Composition.*

At the time of the original examination the "calcitic andesite," underlying the West End rhyolite sheet, was included with the formation above this sheet, as the "calcitic phase of the earlier andesite." This "calcitic andesite" has now been found to be a distinct and younger formation. This elimination leaves us free to consider from a new viewpoint the rocks certainly remaining in this oldest formation, originally characterized as "earlier andesite." These rocks, especially when altered, are often distinguishable with difficulty from the "later andesite" and have a typical andesitic appearance; but large masses of the formation have a greenish glassy or semi-glassy groundmass, a light color,




Geologic Section A–A′, Tonopah Belmont Mining Co. of Nevada. Geology by J. E. Spurr, assisted by J. A. Burgess.

and a faint flow-banding, strongly suggestive of a more siliceous type of rock.

As all of this rock has been altered (by the waters accompanying mineralization), and much of it intensely; and as the result of this alteration has been a progressive increase of silica and potash, with diminution of other constituents, these more siliceous-appearing types were at first regarded as owing their peculiarities to this alteration.

Of the various specimens of "earlier andesite" analyzed (and selected for their freshness) the following four were, after attendant microscopic examination, selected as comparatively little altered rocks:

| | 18 | 19 | 20 | 23 |
|---|---|---|---|---|
| $SiO_2$ | 66.15 | 66.77 | 67.18 | 69.13 |
| $Al_2O_3$ | | 18.01 | 18.50 | 16.51 |
| $Fe_2O_3$ } | 3.17 | 1.94 | 3.86 | 1.50 |
| FeO } | | 1.01 | 0.58 | 0.82 |
| CaO | | 0.59 | 0.40 | 0.36 |
| MgO | | 1.33 | 0.79 | 0.51 |
| $Na_2O$ | 2.38 | 2.99 | 1.82 | 2.80 |
| $K_2O$ | 5.48 | 5.22 | 5.38 | 4.74 |

No. 18 600 Level Mizpah Mine
19 400 Level Stone Cabin
20 615 Level Montana
23 500 Level Mizpah Mine

These rocks show under the microscope a glassy to microlitic groundmass, with scattering crystals of orthoclase and striated feldspar, partly altered to quartz, sericite, and occasionally calcite; and sparse crystals of biotite, uniformly present and always bleached with the development of pyrite, and sometimes chlorite. The groundmass is slightly attacked by silicification, and shows nests and irregular veins of fine quartz. It seems evident, however, that the chemical composition is not much different from the original one. The analyses of these rocks are quite uniform, and the three complete analyses may be averaged as follows:

| | |
|---|---|
| $SiO_2$ | 67.69 |
| $Al_2O_3$ | 17.67 |
| $Fe_2O_3$ | 2.43 |
| FeO | 0.80 |
| CaO | 0.45 |
| MgO | 0.88 |
| $Na_2O$ | 2.54 |
| $K_2O$ | 5.11 |
| | 97.57 |

These analyses represent a rock with the soda-lime feldspars almost wanting, as in typical rhyolites and trachytes; and with the alkali feldspar predominantly potassic—*i. e.*, orthoclase. The silica percentage is somewhat high in proportion to the alkalies, and is about between the rhyolites and the trachytes, suggesting that the rock is a rhyolite-trachyte. Since, however, primary free quartz is practically never detected, either in the hand specimen or under the microscope, in this rock, and as even the least altered specimens show under the microscope a little silicification it is probable that the excess silica in the analyses is mainly due to this secondary action; and that the rock was probably originally a typical orthoclase rock—trachyte; and with this conclusion the appearance and composition of the rock accord.

Analysis of a specimen of this rock from the Mizpah Extension mine shows a somewhat higher lime content:

| | |
|---|---|
| $SiO_2$ | 65.5 |
| $Al_2O_3$ | 17.5 |
| FeO | 1.8 |
| $Fe_2O_3$ | 0.1 |
| $FeS_2$ | 2.6 |
| CaO | 1.7 |
| MgO | 1.5 |
| $Na_2O$ | 2.8 |
| $K_2O$ | 6.0 |
| | 99.5 |

Mizpah Extension sample from 1,160-level east, cross-cut 152 feet east of station 51. Analyzed by Booth, Garret & Blair, December 31, 1913.

This analysis indicates a larger representation of the soda-lime feldspars, which indication is corroborated by microscopic study of rocks from the same vicinity.

Further alteration of the rock is attended by increase of silica and by a slight increase in potash, so that the rock assumes the chemical composition of rhyolite varying much in silica content; but these more siliceous rocks show both under the microscope and to the naked eye the proof of their silicification.

The "earlier andesite," having, then, been subdivided into an andesitic and a trachytic rock, the original term has been dropped, and the principal ore-bearing formation referred to as the "Mizpah trachyte."

*Composition and Structure.*

The Mizpah trachyte shows frequent flow-structure, especially toward the base, where it has a conspicuous and characteristic grayish-green glassy groundmass in which are contained the feldspar phenocrysts and the relatively sparse phenocrysts of the ferromagnesian minerals. Elsewhere it often develops a better crystallization with increase in the proportion of the phenocrysts and decrease of the groundmass. Biotite frequently becomes more conspicuous in such cases, and the appearance of the rock is quite different from that of the semi-glassy phases just described, and becomes difficult to distinguish from the Midway andesite. In certain localities, as in the Red Plume property of the Tonopah Mining Company. flowbreccia bands of this andesite occur in the normal solid rock. Whether this indicates that the Mizpah trachyte consists of a number of successive flows is uncertain; there is at least no definite evidence to prove this, and to disprove the possibility that the breccias may not be flow-breccia layers in a single very thick flow. It is this view that the writer inclines to, in default of definite evidence to the contrary, and after an unsuccessful effort to separate the Mizpah trachyte into distinct members.

*Alteration.*

The Mizpah trachyte is the enclosing rock of the principal productive veins, and is usually much altered. The most conspicuous results of this alteration are quartz, sericite, and fre-

quent adularia, with in some places considerable calcite, chlorite, pyrite and siderite.

*Thickness.*

The Mizpah trachyte has a maximum thickness of about 700 feet on Mizpah hill,, where it outcrops. The original thickness must have been considerably greater; the upper part has been stripped off by erosion.

*Age.*

The Mizpah trachyte passes by transition into the "Glassy trachyte" below, showing that the glassy trachyte was a lower or possibly even basal phase of this great mass, which is thus shown to have the character of a surface flow. These two rocks, considered jointly, represent the oldest known formation of the camp with the possible exception of certain andesite blocks, so far found only as inclusions in the younger intrusive rocks. Various satisfactory and convincing intrusive contacts of the West End rhyolite into the Mizpah trachyte were found, especially on the 5th level Montana and the 800, 900 and 1,000 levels of the Belmont (Fig. 99). Striking intrusive contacts of the underlying sheet of andesite (Sandgrass or "calcitic andesite") into the "Glassy trachyte" are found in the Midway mine (Pl. XXIV., Fig. 1), and the main mass of later (Midway) andesite normally overlies the "Mizpah trachyte" and its veins as a barren cap-rock. The Tonopah rhyolite forms a conspicuous dike in the Mizpah trachyte and Glassy trachyte on the 900-foot level of the Belmont (Fig. 99).

### THE GLASSY TRACHYTE.

*Definition.*

This formation was very little developed at the time of the original investigation. Underlying the normal "Mizpah trachyte," it does not outcrop. What few patches were noted at first were regarded as phases of the rhyolitic intrusives. But subsequent investigation showed that the rock passes upward by

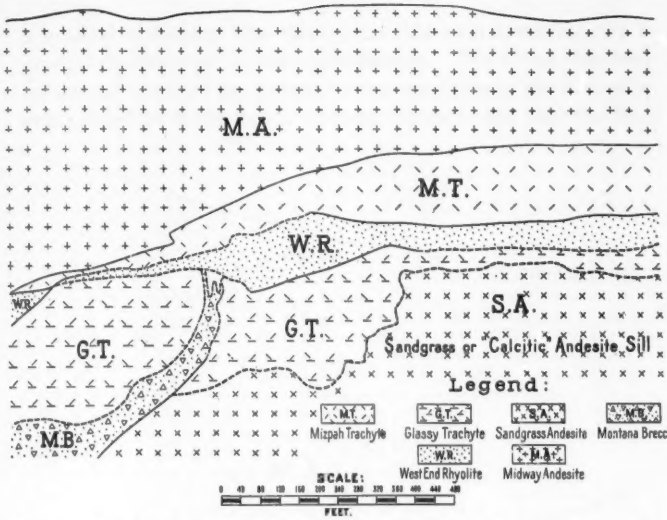



FIG. 1. Geologic Section A–A', Tonopah Midway Mining Company. Geology by J. E. Spurr, assisted by W. H. Grant.

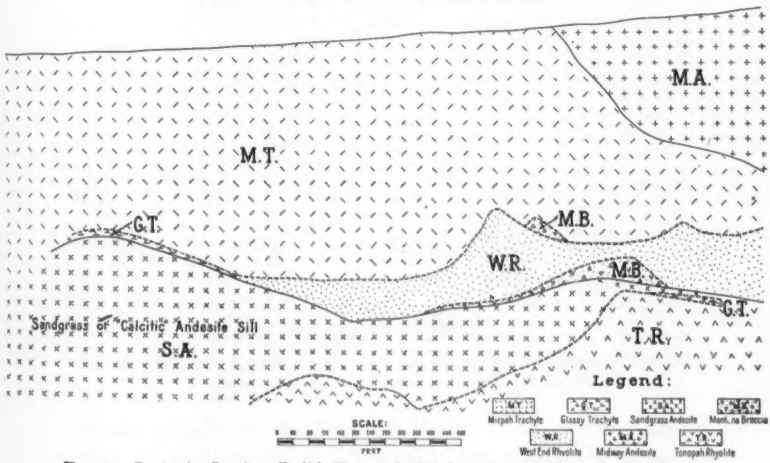
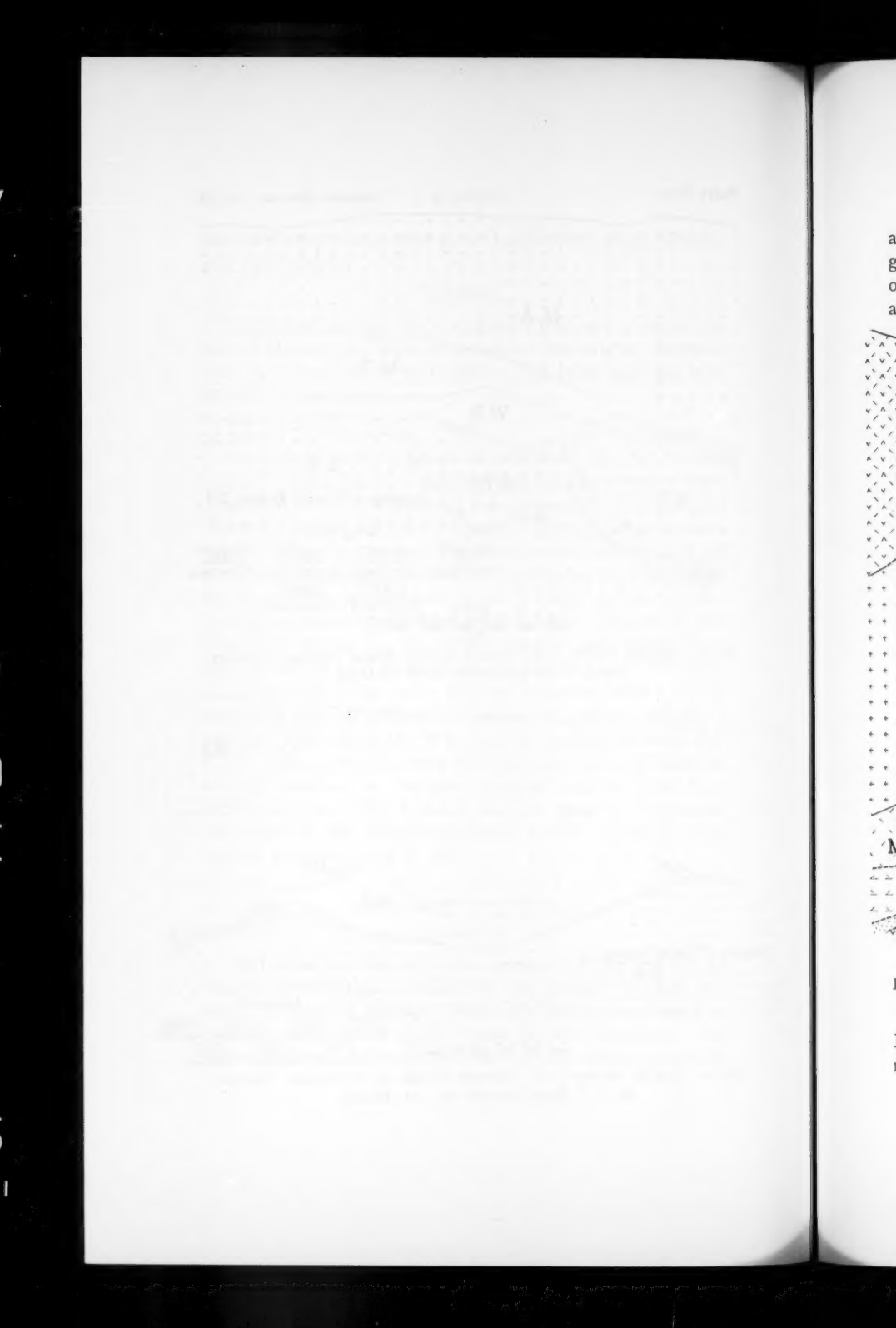



FIG. 2. Geologic Section D–D', Tonopah Mining Co. of Nevada. Geology by J. E. Spurr, assisted by J. A. Burgess.



a gradual transition into the typical "Mizpah trachyte," by a gradual development of the crystallization. This is best observed on several levels of the Belmont mine, particularly the 800, 900, and 1,000-foot levels, but is also observable in and near the Red

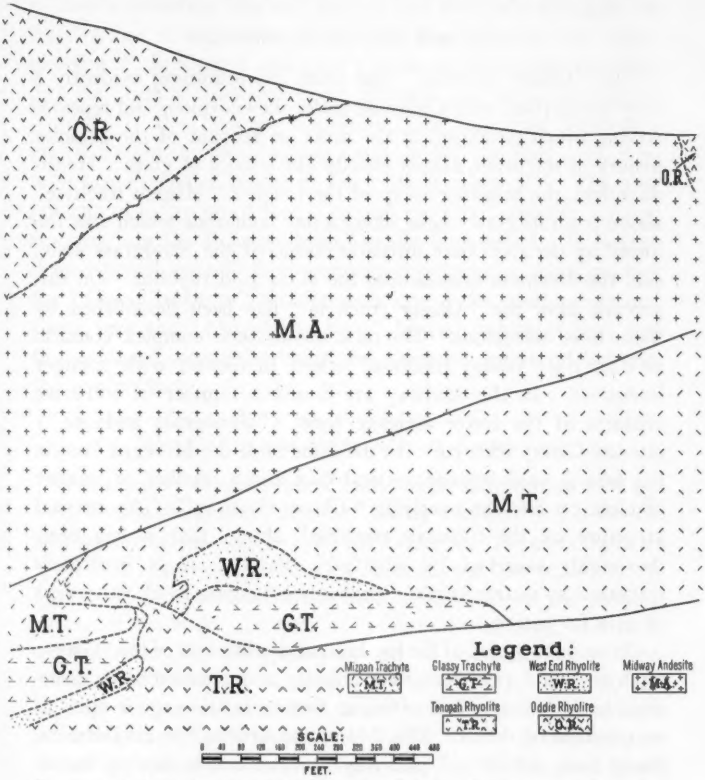



FIG. 99. Geologic Section C–C', Tonopah Belmont Development Company. Geology by J. E. Spurr, assisted by W. H. Grant.

Plume property of the Tonopah Mining Company, particularly near the shaft on the 700-foot level; and also in the Montana.

In most places, however, the "Glassy trachyte" is separated from the "Mizpah trachyte" proper by the intrusive West End rhyolite sheet, which has been inserted principally along the zone of transition between the two rocks.

*Age and Physical Peculiarities.*

The "Glassy trachyte" was from the beginning evidently a very brittle rock, which behaved under the enormous and repeated strains which developed in the rocks on account of the complex history of intrusion, almost exactly like a block of glass. Hence, doubtless, the breaking away of the tougher "Mizpah trachyte" above from its glassy base, along a flat fault-zone which was followed by the successive intrusive sheets of the Sandgrass andesite, the Montana breccia, and the West End rhyolite. On this account also, the "Glassy trachyte" has been demolished by these later intrusions. No rock shows such complex contacts as does the "Glassy trachyte" where in contact with younger intrusives. In the Midway are found a number of intrusive contacts of the lower andesite sheet ("Sandgrass andesite") into the Glassy trachyte. In the same mine the Montana breccia has sent a small regular vertical dike and a number of smaller dikelets, up into the overlying "Glassy trachyte." The internal structure of the "Glassy trachyte" shows that it has been thoroughly searched by silicifying waters. It is intricately traversed by quartz veinlets, probably belonging to all the stages of vein formation.

On account, again, of the hardness and brittleness of the "Glassy trachyte," it forms numerous angular and characteristic inclusions in the younger intrusives, so that its relative age is open to no question of doubt. The "Montana breccia" is an intrusive glassy rock, which will presently be described as having immediately preceded the West End rhyolite intrusion. This Montant breccia intrusion is full of angular inclusions of the rocks which it met and demolished in its path. Most abundant among these inclusions are those of the "Glassy trachyte," varying in

size from fine grains to blocks several feet in diameter. This may be observed in many places, as on the 765-foot level of the Montana and in the Tonopah Extension. Angular inclusions of the "Glassy trachyte" in the West End rhyolite, although by no means abundant, are well-known, and definitely establish the relative age of these two rocks. As already stated, the lower andesite ("Sandgrass andesite") sheet is intricately intrusive into the "Glassy trachyte" in the Midway, and the same relation is found in the Tonopah Extension; and the same Sandgrass andesite sheet, at the Montana shaft on the 765-foot level, contains large included blocks of the "Glassy trachyte." The phenomena of intrusion of the "Tonopah rhyolite" into the "Glassy trachyte" in the Belmont have already been noted. It is thus demonstrated entirely from comparative intrusive relations that the "Glassy trachyte" is older than any of the other recognized rocks save the "Mizpah trachyte" beneath which it lies; and this evidence harmonizes with the observed transition between the two rocks.

### *Silicification and Barrenness of Formation.*

It is a matter of observation, based upon considerable development work underground, that the "Glassy trachyte" is not an ore-bearing formation—not even to the extent that the certainly later West End rhyolite is. This is a circumstance that would hardly have been expected, and must have resulted from the physical nature of the rock. In spite of its intense shattering and thorough silicification, unequalled by any of the other formations, definite, well-bounded veins are characteristically lacking, and little or no pay-ore has been found within it, to the writer's knowledge; although pay-ore belonging to the period of ore-deposition subsequent to the West End rhyolite has been found along flat fault-contacts between the Glassy trachyte and the West End rhyolite.

The reason for this circumstance may be as follows: All the phenomena of the study of mineral veins, of the shallow-seated

Tertiary class which we are discussing, combine to indicate that they were formed from solutions carrying relatively small proportions of the metals. Where the channels along which these solutions circulated through the rigid rocks created physical conditions which favored precipitation of metals, there an ore-body was formed, each passing gallon of solution contributing its mite till the net result reached large proportions. The earthy materials with which the solutions were charged were mostly carried onward past the locus of metal-deposition, to be deposited as barren veins, or as replacements (chiefly silicification) of the wall-rock. In the original discussion by the writer of the origin of the veins in the Mizpah trachyte at Tonopah, it was pointed out that the metals were precipitated from the solutions in the circulation channels offered by definite fracture-and-fissure zones; that the wall-rocks of these zones, in part *by their reactions with the mineralizing solutions,* acted as a screen, through which the metals did not pass, but through which the earthy materials in solution, especially silica and to a less extent potash, passed in abundance, leaving the associated metals in the fissured zone and producing barren silicified trachyte encasing the veins.[3]

In the case of a rock thoroughly shattered and fissured, and offering an immense amount of opening to the same solutions, such a physico-chemical separation of the dissolved constituents would not be brought about to any marked extent; and the tendency would be for the scanty metals and the greatly excess silica to remain together up to the point of precipitation, with the result that the precipitated quartz would contain so little metals that it could not be classed as ore, especially if with it were included a great quantity of shattered rock. This was apparently the case with the "Glassy trachyte."[4]

This consideration is also probably at the root of the explanation why as a broad and general rule, the richness of the ore in

[3] Prof. Paper No. 42, pp. 226, 234, 237.

[4] Since the above was written, Mr. Frederick H. Bradshaw, manager of the Belmont, has informed the writer that he has discovered in the Belmont a locality where a great mass of the silicified Glassy trachyte carries values of around $3, which figure is unfortunately well below the pay limit.

any district is apt to vary inversely as the width of the vein. It may also explain why in many small fissure veins there is often a layer of nearly solid sulphides or even of metal (in the case of gold) along the walls, while the center is occupied by the usual metalliferous quartz.

### *Thickness.*

Very little of the Glassy trachyte that is recognizable is left in the Mizpah and the Montana mines, save in small blocks. In the Desert Queen shaft of the Belmont mine, however, it has a thickness of about three hundred feet, and in the Midway at least 250 feet is indicated.

### *Sandgrass or "Calcitic" Andesite.*

An intrusive sheet of andesite is found in depth in some of the principal mines, usually underlying all of the other rock formations described with the exception of the deep-seated intrusive mass of Tonopah rhyolite breccia. The locus of intrusion of this sheet seems to have been determined by the same factor that influenced the intrusion of the Montana breccia and the West End rhyolite—the brittleness of the "Glassy trachyte," which rendered it an especially easy zone of intrusion, as the detailed study of the contacts in the Midway mine testifies.

The thickness of the Sandgrass andesite intrusion is evidently greatest in the northwestern part of the producing area, as indicated by the developments in the MacNamara and Tonopah Extension mines. Its lower limit has not been determined in this region, but the total thickness may well be 500 feet or more. To the southeast the intrusion rises with a ragged contact against the "Glassy trachyte," and thins rapidly in the direction of the Belmont mine (Pl. XXIV., Fig. 2). At the Montana shaft the thickness is only about 40 feet.

The Sandgrass andesite was originally correlated by the writer with the "earlier andesite" and called the "calcitic phase of the earlier andesite," whence the local name of "calcitic andesite."

In 1910, in a report not published by the writer, but which was printed by the Montana Tonopah mine for private circulation, it was referred to the "later" (Midway) andesite period. The investigations of 1914 and 1915 have established the fact that it is intermediate in age between the two.

The Sandgrass andesite is intricately intrusive into the "Glassy trachyte" on several levels of the Midway mine (cf. Pl. XXIV., Fig. 1) and it also in one place includes a large block of the Mizpah trachyte. In the Buckeye it is also found intrusive into the Glassy trachyte (specimen shown by George H. Garrey). In the Montana Tonopah, Sandgrass and Tonopah Extension, the Sandgrass andesite is found intruded by the Montana breccia, which is itself intruded in these mines by the West End rhyolite. In the Buckeye, 1,200-foot level, Mr. George H. Garrey has mapped and described to the writer an intricate intrusive contact of West End rhyolite into the Sandgrass andesite, with flow-banded marginal phase of the rhyolite, tongues of rhyolite in the andesite, and inclusions of andesite in the rhyolite. The age of the Sandgrass andesite is thus finally fixed as later than the Mizpah trachyte and Glassy trachyte, and earlier than all the other described rock-formations. It was also evidently later than the veins of the first period, which were formed after the trachyte eruption; for these veins do not pass downward from the trachyte into the andesite.

The Sandgrass andesite was originally a hornblende-biotite andesite, but as now found is always highly altered. The chemical composition is essentially the same as the Midway andesite (see table of analyses, p. 731).

The principal secondary products are calcite and chlorite, the former produced chiefly at the expense of the feldspars, the latter from the ferromagnesian minerals. Pyrite and siderite are common. Locally, however, this rock is chiefly altered to quartz and sericite, has undergone considerable silicification, and even contains considerable silicified zones or quartz veins giving assays of a few dollars to the ton. The Sandgrass andesite locally forms the footwall of the (second period) Sandgrass vein

## TABLE OF ANALYSES FOR TONOPAH ROCKS.

### Mizpah Trachyte.

| No. | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | CaO | MgO | $Na_2O$ | $K_2O$ | $Fe_2O_3$, FeO, CaO, MgO |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 65.5 | 17.5 | 0.1 | 1.8 | 1.7 | 1.5 | 2.8 | 6.00 | 5.1 |
| 2 | 66.15 | ..... | 3.17 | | ..... | ..... | 2.38 | 5.48 | ..... |
| 3 | 66.77 | 18.01 | 1.94 | 1.01 | 0.59 | 1.33 | 2.99 | 5.22 | 4.87 |
| 4 | 67.18 | 18.50 | 3.86 | 0.58 | 0.40 | 0.79 | 1.82 | 5.38 | 5.63 |
| 5 | 68.68 | ..... | 3.06 | | ..... | ..... | 0.21 | 6.17 | ..... |
| 6 | 69.13 | 16.51 | 1.50 | 0.82 | 0.36 | 0.51 | 2.80 | 4.74 | 3.19 |
| 7 | 71.14 | 15.24 | 1.77 | 0.26 | 0.09 | 0.16 | 0.24 | 6.31 | 2.28 |
| 8 | 72.98 | 14.66 | 1.01 | 0.16 | 0.18 | 0.33 | 0.00 | 6.03 | 1.66 |
| 9 | 73.50 | 14.13 | 1.51 | 0.26 | 0.12 | 0.21 | 0.24 | 5.11 | 2.10 |
| 10 | 76.25 | 12.84 | 0.54 | 0.33 | 0.16 | 0.56 | 0.12 | 3.20 | 1.57 |

### Glassy Trachyte.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 71.79 | 15.24 | 2.00 | 0.10 | Tr. | 0.08 | 1.21 | 5.51 | 2.18 |
| 2 | 72.27 | 16.38 | 1.96 | 0.19 | Tr. | 0.49 | 0.22 | 3.71 | 2.64 |
| 3 | 75.44 | 13.77 | 0.80 | 0.05 | Tr. | Tr. | 0.27 | 6.39 | 0.85 |
| 4 | 75.45 | ..... | 0.78 | | ..... | ..... | 1.12 | 5.74 | ..... |

### Sandgrass Andesite.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 53.57 | ..... | 6.67 | ..... | ..... | ..... | 2.75 | 5.63 | ..... |
| 2 | 54.10 | 19.41 | 3.50 | 2.86 | 4.81 | 2.94 | 2.68 | 4.66 | 14.11 |
| 3 | 55.60 | 16.70 | 2.23 | 3.51 | 4.27 | 2.60 | 4.08 | 3.17 | 12.61 |
| 4 | 56.40 | 20.12 | *0.09 | 5.87 | 3.55 | 1.99 | 4.87 | 2.56 | 11.50 |
| 5 | 61.65 | 18.64 | 2.96 | 2.61 | 0.29 | 2.73 | 2.74 | 3.98 | 8.59 |

### West End Rhyolite.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 72.50 | ..... | 0.89 | | ..... | ..... | 0.25 | 4.90 | ..... |
| 2 | 73.20 | 14.59 | ..... | 1.92 | 0.47 | 1.24 | 0.12 | 4.32 | 3.63 |
| 3 | 77.02 | 13.81 | 0.97 | 0.09 | Tr. | 0.15 | 0.31 | 5.12 | 1.21 |
| 4 | 77.30 | 13.79 | 0.87 | 0.14 | 0.10 | 0.05 | 0.22 | 4.22 | 1.16 |

### Midway Andesite.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 43.00 | 16.49 | 2.86 | 6.31 | 5.69 | 6.19 | 0.12 | 0.84 | 21.05 |
| 2 | 51.64 | 15.58 | 0.16 | 0.58 | 6.25 | 2.79 | 0.27 | 2.46 | 9.78 |
| 3 | 53.05 | 16.22 | 0.90 | 3.67 | 5.37 | 4.83 | 1.00 | 4.00 | 14.77 |
| 4 | 53.84 | 18.92 | 2.37 | 3.24 | 6.04 | 3.25 | 1.02 | 1.72 | 14.90 |
| 5 | 56.26 | 16.18 | 5.56 | 1.17 | 5.07 | 2.78 | 3.23 | 3.43 | 14.58 |
| 6 | 56.70 | 17.01 | 2.58 | 1.19 | 5.27 | 2.17 | 2.33 | 3.04 | 11.21 |
| 7 | 56.72 | ..... | 5.58 | | ..... | ..... | 2.72 | 3.94 | ..... |
| 8 | 56.89 | 18.25 | 3.20 | 2.15 | 4.03 | 2.93 | 2.00 | 3.05 | 12.31 |
| 9 | 57.04 | 16.55 | 2.27 | 3.00 | 3.08 | 2.14 | 2.62 | 3.15 | 10.49 |
| 10 | 57.51 | 16.55 | 3.20 | 2.02 | 6.06 | 2.30 | 2.76 | 2.81 | 13.58 |
| 11 | 59.03 | 20.61 | 1.09 | 3.27 | 3.86 | 2.29 | 1.40 | 2.23 | 10.51 |
| 12 | 60.53 | 17.89 | 4.14 | 0.77 | 3.13 | 1.63 | 2.05 | 4.06 | 9.67 |
| 13 | 61.23 | 16.45 | 5.17 | 0.29 | 2.79 | 1.83 | 2.53 | 2.61 | 10.08 |

### Brougher Rhyolite-Dacite.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 71.71 | 14.00 | 1.06 | 0.51 | 2.25 | 0.43 | 3.21 | 4.41 | 4.25 |
| 2 | 73.00 | ..... | ..... | ..... | 1.55 | ..... | 3.50 | 4.71 | ..... |
| 3 | 75.56 | ..... | ..... | ..... | 1.16 | ..... | 4.20 | 4.50 | ..... |

TONOPAH RHYOLITE.

| No. | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | CaO | MgO | $Na_2O$ | $K_2O$ | $Fe_2O_3$, FeO, CaO, MgO |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 68.86 | 16.33 | 2.21 | 0.38 | 1.30 | 0.68 | 1.76 | 5.00 | 4.57 |
| 2 | 72.31 | 13.79 | 1.54 | 0.26 | 1.08 | 0.56 | 2.56 | 4.66 | 3.44 |
| 3 | 75.17 | 15.83 | *0.17 | 0.90 | 0.46 | 0.39 | 2.08 | 3.18 | 2.92 |

ODDIE RHYOLITE.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 75.66 | ..... | ..... | ..... | 0.47 | ..... | 1.70 | 4.94 | ..... |
| 2 | 76.57 | ..... | ..... | ..... | ..... | ..... | 0.96 | 5.81 | ..... |

BASALT.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 53.94 | ..... | ..... | ..... | 7.32 | ..... | 3.89 | 2.09 | ..... |

*Localities.*—Mizpah Trachyte: 1, Mizpah Extension, 1,160-foot level east, cross-cut 152 feet east of Sta. 51; 2, 600 Mizpah; 3, 400 Stone Cabin; 4, 615 Montana; 5, 300 Mizpah; 6, 500 Mizpah; 7, near Mizpah Hill; 8, Lease 86, Mizpah Mine, 180-foot level; 9, Mizpah Hill; 10, Wall of Mizpah Vein.

Glassy Trachyte: 1, 1,170 Belmont, S 2580, W 865; 2, 765 Montana, N 9880 E 9555; 3, Belmont mine, breast of cross-cut south from D.S. shaft; 4, 700 Red Plume, 60 feet s. from shaft.

Sandgrass Andesite: 1, 700 Red Plume; 2, 900 Mizpah; 3, Mizpah shaft, 670 feet from collar; 4, 700 Mizpah, 100 feet east of Brougher shaft; 5, 765 Montana, at station N 9912, E 9588.

West End Rhyolite: 1, 600 Mizpah, east end of level; 2, 600 Mizpah, D 611; 3, 600 Mizpah, at station; 4, 600 Red Plume, cross-cut 603 N of D 609.

Midway Andesite: 1, Montana Tonopah shaft; 2, North Star shaft, 350 feet from collar; 3, Sandgrass, D.H. 11, 809 feet from surface; 4, 300 Mizpah; 5, Halifax shaft, 275 feet from collar; 6, 515 Montana, N 10150, E 10200; 7, 500 Red Plume, S 2700, W 3370; 8, 500 Mizpah; 9, 765-Montana, north end of cross-cut; 10, Mizpah Extension shaft, 245 feet from collar; 11, Sandgrass, D.H. 12, 805 feet from surface; 12, 400 Red Plume; 13, 515 Montana, N 10270, E 8690.

Brougher Rhyolite-Dacite: 1, Brougher Mountain; 2, Butler Mountain; 3, Golden Mountain.

Tonopah Rhyolite: 1, 1,500 Mizpah; 2, 2,700 feet north of King Tonopah shaft; 3, 1,200 Mizpah, at station.

Oddie Rhyolite: 1, Belmont shaft; 2, G. & H. Tunnel, Mt. Oddie.

Basalt: 1, Siebert Mountain (not typical basalt).

*Analysts.*—Mizpah Trachyte: 1, 2, 3, 4, 5, and 6, Booth, Garrett & Blair; 7, 8, 9, and 10, George Steiger. Glassy Trachyte: 1, 2, 3, and 4, Booth, Garrett & Blair. Sandgrass Andesite: 1, 2, and 5, Booth, Garrett & Blair; 3, George Steiger; 4, Prof. G. J. Young. West End Rhyolite: 1, 3, and 4, Booth, Garrett & Blair; 2, Prof. G. J. Young. Midway Andesite: 3, 4, 6, 7, 8, 9, 11, 12, and 13, Booth, Garrett & Blair; 1 and 10, George Steiger; 2 and 5, Dr. W. F. Hillebrand. Brougher Rhyolite-Dacite: 1, George Steiger; 2 and 3, Dr. E. T. Allen. Tonopah Rhyolite: 1, Booth, Garrett & Blair; 2, George Steiger; 3, Prof. G. J. Young. Oddie Rhyolite: 1 and 2, Dr. E. T. Allen. Basalt: 1, Dr. E. T. Allen.

in the Sandgrass, and elsewhere may wholly enclose large quartz veins. Nevertheless, as far as pay-ore is concerned, it has hitherto proved an almost entirely barren formation.

The usual texture of the Sandgrass andesite is finer than that of the Midway andesite, and it locally has a faint brecciated structure, probably due to autobrecciation during flowage.

### THE MONTANA BRECCIA.

#### *Description.*

A breccia whose exact nature and relations were for a long time puzzling has a widespread distribution in the underground workings, having been studied by the writer in the Montana, Belmont, Mizpah (Tonopah Mining Company), Midway, Mizpah Extension, and Tonopah Extension mines. It is closely associated with the West End rhyolite, and frequently occurs as a zone of variable thickness along the upper or the lower contact, or both contacts, of this rock. It also occurs as independent masses of considerable size, though always close to the West End rhyolite. The 765-foot level of the Montana has developed a large mass of this breccia; and what is probably the same body is developed in the Midway, the Merger, the Tonopah Extension, and the Sandgrass.

This rock is full of foreign angular inclusions, which are frequently so abundant as to obscure the groundmass. In many other places the groundmass can be seen to be a greenish or brownish glass, evidently rhyolitic. The most abundant included rock is the "Glassy trachyte," which often forms so large a part of the mass that it is doubtful whether the result should be classified as Glassy trachyte with intense intrusion of breccia or breccia with an inordinate amount of trachyte inclusions. Small typical dikes of the Montana breccia into the Glassy trachyte may also be found, as in the Tonopah Extension. Where in contact with the Mizpah trachyte, abundant inclusions of this rock are also frequently observed. There are also inclusions of Sandgrass andesite, and a large variety of rhyolitic and andesitic

rocks strange to the locality, and apparently derived from the depths, and even occasionally of shale (Montana Tonopah mine), derived probably from deep-seated Paleozoic rocks below.

In many places the greenish glass matrix of the Montana breccia is entirely aphanitic, and resembles that of the West End rhyolite; elsewhere small rounded (corroded) quartz phenocrysts are plentifully present, as was especially noted in the Sandgrass, the Tonopah Extension, and the Mizpah Extension.

These phases showing quartz phenocrysts may easily be confused with the Tonopah rhyolite breccia, the matrix of which is a rhyolitic glass altogether similar, as far as the eye can determine, with the glassy matrix of the Montana breccia; and the writer has made some mistakes in taking one of these rocks for the other, which have subsequently been corrected. Distinction between the two is important, and unfortunately no rule can be given. The Montana breccia is noteworthy for the great abundance of its foreign inclusions, especially of Glassy trachyte, while the Tonopah rhyolite, as will presently be described, is essentially an autoclastic breccia, the fragments in which represent earlier congealed portions of the same rock.

### *Occurrence.*

Cross-sections through the Midway, the Tonopah Extension, and the Sandgrass, show that the intrusive sill of Montana breccia, which in general was thrust between the Sandgrass andesite below and the Mizpah trachyte above (in places completely demolishing the Glassy trachyte formation and incorporating it into the igneous breccia), has, throughout the western portion of the camp, at least, the shape of a wedge, with the narrow point upward. This upward point probably terminates in the ground of the Tonopah Mining Company and the West End and probably never reached the surface; but below the wedge thickens greatly, as it passes down into the Merger, with a general dip of around 30°, which is also roughly the general inclination of the associated rock formations. The lower part of the wedge

has a thickness of several hundred feet, and its extension in depth to the north is unknown.

At the east end of the camp, in the Mizpah Extension mine, the Montana breccia is also largely represented, occupying the same close relations to the Glassy trachyte horizon.

### *Dynamics of Intrusion.*

In the dikelets of Montana breccia which intrude other rocks, and even in some of the dikes up to several inches thick, an interesting phenomenon is noted. The included fragments are partially or even entirely eliminated and the intrusive tongue consists entirely of the greenish glass. Plainly the passages in the intruded rock through which the lava had to pass were too narrow to admit the passage of even the very small inclusions, which were thus filtered out. That under these circumstances the lava could still pass through shows how fluid it was at the time of intrusion; and the fact that this filtered lava is now found occupying dikes sometimes several inches across supplies food for reflection on the mechanics of intrusion. It would seem that the pressure exerted by this liquid had been sufficient to have enlarged manyfold the width of the opening into which it has been admitted. As to the highly liquid character, at the time of intrusion, of the lava which forms the matrix of the Montana breccia, the contact relations with the Glassy trachyte, above referred to, leave no doubt; for here the lava has penetrated even the tiniest visible fissures.

On a larger scale the same reflections are suggested by a consideration of the whole intrusion of the Montana breccia into the shattered Glassy trachyte along the general horizon between the Sandgrass andesite and the Mizpah trachyte. Although the quick chilling of the intrusive lava into glass indicates cold intruded rocks and inferentially a shallow depth, yet several hundred feet of the overlying Mizpah trachyte must have been lifted up, at least locally, by this liquid.

*Comparison with Dynamics of Quartz Vein Injection.*

The phenomena resemble those attendant upon the formation of certain metalliferous quartz veins of this and other districts, which occupy frequently very large spaces which could not possibly have been open before the injection or intrusion of the vein-forming solutions.

Take the case in Tonopah, for example, of the great West End-MacNamara vein, which in its initial form consisted of a persistent zone of low grade quartz of great thickness, reaching up to twenty feet or more in thickness. While this quartz has intricately penetrated the wall rocks, yet substantially the main vein bears the evidence of having filled a fissure, and little or none of having been formed by replacement. The dip of this vein is flat and in the vicinity of the West End-MacNamara mines is arched up to form a partially developed dome, with dips to the north, south, and east. The writer cannot conceive that a fissure of this persistence and width was open to receive the solutions which deposited the quartz; such an opening would have offered no resistance to the direct weight of the overlying rocks. The natural conclusion seems to be that the opening was made by the pressure of the siliceous solutions, which forced their way along the old line of weakness (originally due to the fragility of the Glassy trachyte and successively reopened by the intrusion of the several igneous sills and by fault movements following the same general zone) under pressure sufficient to lift the overlying rocks and support them until the solutions crystallized into quartz. The difference between the dynamics of the intrusion of the alaskitic Montana breccia and the subsequent trachy-alaskitic West End rhyolite, and those of the still later West End-MacNamara vein (which followed the West End rhyolite intrusion) seems to have been a difference in degree rather than kind. The writer long ago came to this conclusion as regards certain deep-seated veins;[5] and now it seems applicable to certain shallow-seated ones. In connection with the latter, however, as

[5] At Silver Peak, Nevada. Prof. Paper No. 55, U. S. G. S., p. 113.

exemplified by the West End and other thick, relatively flat veins of the Tonopah district, it is noteworthy that the lines of weakness along which they penetrated apparently never reached the surface; so that relief of pressure was not possible, as it would be in the case of solutions ascending along steeply inclined fissures connecting with the surface.

### *Relative Age.*

In the Belmont mine (1,000-foot level) the Montana breccia shows in several places clean-cut and decisive intrusive contacts into the Mizpah trachyte. In a number of places, as on the 500-foot level Mizpah (Fig. 100), the 515- and 765-foot levels of the Montana, and the 900-foot level Belmont, clean-cut intrusive contacts of the West End rhyolite into the Montana breccia are found; in the case of the Montana 765-foot level the former sends out dikes into the latter. This sharp contact between the two rocks is often found even where the Montana breccia occurs as a narrow band lying between the West End rhyolite and the Mizpah trachyte, as for example on the 515-foot level Montana.

In the Montana, the Tonopah Extension and the Sandgrass contacts between the Montana breccia and the Sandgrass andesite are found, and in all cases the phenomena show that the former is intrusive into the latter. Near the contact the breccia includes many fragments of the andesite, and at the contact it sends out dikelets of glass into the andesite.

In the Mizpah Extension, a very important contact between the Montana breccia and the Tonopah rhyolite breccia was pointed out by Supt. A. H. Lawry. The data indicate that the Tonopah rhyolite is the younger; it is finely flow-banded for a fraction of an inch at the contact, which is sharp, sinuous, and normal.

## THE WEST END RHYOLITE.

### *Description.*

The West End rhyolite is an unusually uniform and characteristic rock, of a peculiar green color, and containing inclusions of

some rock now altered to a white powdery state. It is massive, with occasional inconspicuous flow-banding, and is highly altered. Phenocrysts are rare and small, and include feldspar and

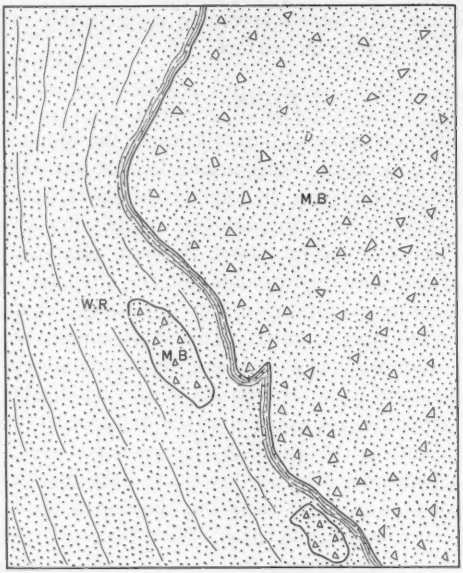



FIG. 100. Tonopah Mining Co., 500-foot level, Mizpah. Sketch showing intrusive contact of West End rhyolite (W. R.) into Montana breccia (M. B.). The rhyolite has vertical flow-structure as indicated, growing intense near the contact.

biotite, both highly altered, and quartz. The alteration has produced abundant quartz, sericite and kaolin, together with calcite, chlorite, adularia and pyrite. The white inclusions have in nearly all cases been sericitized till they retain no original characteristics.

Some unusually large specimens of these inclusions have been found in the Tonopah Extension mine. The inner portions are a fresh brown rhyolitic rock, aphanitic to the naked eye, which in

a zone following the periphery has been altered to the typical white powdery condition. This alteration was plainly the direct effect of reagents in the hardening matrix.

The exact nature of this matrix thus becomes a subject of interest. Contact phenomena show beyond doubt that it behaved in all respects as an intrusive rock. The microscope frequently shows a fine internal brecciation, with angular inclusions of both rhyolite and andesite, in a groundmass "so variable in granularity and texture that it would be difficult to decide which is the original lava rock and which is inclusion."[6] Along the normal contacts of this rock with other rocks, there is a pronounced fine marginal banding for several inches, parallel to the contact (see Fig. 100); but microscopic work shows this banding to be due to shear rather than normal liquid flow. As many of these contacts seem certainly intrusive contacts of the West End rhyolite, a stiff plastic condition of the rhyolite at the time of intrusion may be inferred. The fine internal brecciation seems to be mainly autobrecciation, as in the case of the Montana breccia and the Tonopah rhyolite; and the shear-flow banding at the contact may be called auto-shear. The apparent sericitization and other alteration of included fragments, by the groundmass or paste, above noted, suggests the presence in this intrusive matrix of heated solutions such as usually follow intrusions, but which here may have been intimately mingled with the intrusive. A condition intermediate between that of a glassy lava which had undergone repeated autobrecciation during flowage, and a volcanic mud, is thus indicated.

### *Relative Age.*

The age of this rock is shown by its contact phenomena, which demonstrate that the rock is intrusive into the Glassy trachyte and the Mizpah trachyte. On the 765-foot level Montana an intrusive contact of West End rhyolite into Mizpah trachyte was traced for over 200 feet. The rhyolite becomes intensely banded for from 6 inches to a foot at the contact, and contains small

[6] Private report of Dr. F. E. Wright to the writer, March 8, 1915.

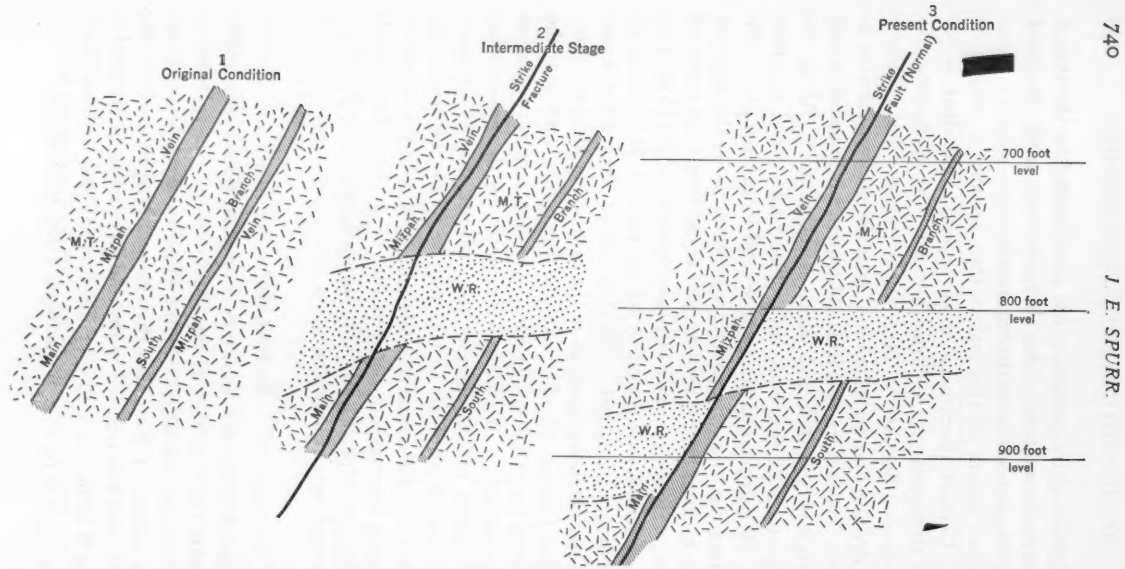



FIG. 101. Diagrams to show history and relations of the Mizpah vein, in the Belmont mine, not far east of the Desert Queen shaft. Scale 100 feet = inch. M. T. = Mizpah Trachyte, W. R. = West end Rhyolite. Fig. 2 shows the horizontal sill of West end Rhyolite intrusive into the Mizpah Trachyte and the first period veins; also the development of a strong fracture plane along the main vein. In Fig. 3 is shown the result of a normal fault movement along this fracture plane, giving the present relations as actually determined by careful mapping.

angular inclusions of the trachyte. This same intrusive rhyolite contact also crosses a vein (belonging to the first period) in the trachyte, and cuts it off cleanly. In the Belmont mine on the 900 and 1,000-foot levels, the same definite intrusive phenomena of the West End rhyolite into the Mizpah trachyte were noted. The intrusion of the West End rhyolite into the "Glassy trachyte" is, as above noted, well shown on the Belmont 800-foot level, and also frequently elsewhere. In the Victor mine (1,550-foot level) small regular dikes of West End rhyolite cut trachyte (approaching the Glassy trachyte in texture), according to Manager John G. Kirchen. A specimen given to the writer shows a regular dike an inch wide, enclosing a fragmnt of the intruded rock.

The intrusive phenomena of the West End rhyolite into the Montana breccia were reviewed in discussing this later rock. In the Buckeye, according to Mr. George H. Garrey, the West End rhyolite shows striking intrusive contacts into both the Montana breccia and the Sandgrass andesite.

*Occurrence.*

The West End rhyolite occurs principally as a single sheet of extremely variable thickness, which has followed the path of the Montana breccia, and occupies approximately the zone between the Mizpah trachyte and the Glassy trachyte. Frequently, as in much of the Mizpah mine, this last-named formation has been submerged by the Sandgrass andesite intrusion, so that this andesite comes into direct contact with the West End rhyolite (Pls. XXIII. and XXIV., Fig. 2). In the Belmont mine, the main rhyolite sheet rises, toward the east, gradually up into the Mizpah trachyte, leaving the transition between the Mizpah trachyte and the Glassy trachyte directly observable; and in the eastern part of the mine the rhyolite appears to split into several sheets, intrusive into the Mizpah trachyte (note Fig. 101). This change of position is also visible in some points at the east extremity of the Mizpah workings, adjacent to the Belmont mine, as at the

end Rhyolite intrusive into the Mizpah Trachyte and the first period veins; also the development of a strong fracture plane along the main vein. In Fig. 3 is shown the result of a normal fault movement along this fracture plane, giving the present relations as actually determined by careful mapping.

east end of the 500-foot level, where Mizpah trachyte was noted beneath the West End rhyolite sheet.

*Thickness.*

The greatest thickness of West End rhyolite is shown in the MacNamara shaft, where it is upwards of 450 feet thick. To the east this sheet thins rapidly till it becomes very thin or perhaps pinches out locally entirely (Pl. XXIII.); but it is found again further to the east at about the same horizon, with an extremely variable thickness. It is probable that in general the thickness tends to diminish toward the east, though locally, as in one point in the Montana, where an intrusive dome or nascent pipe has eaten its way far up into the Mizpah trachyte, the thickness of rhyolite amounts to 350 feet. In the Belmont, however, 50 to 100 feet appears to be the average thickness. The indications are therefore that the intrusion came from the northwest.

The size of the characteristic white inclusions also indicates the same conclusion as to the general source of the intrusion. In the Tonopah Extension (at the west end of the developed zone) they are typically large and are close together, so that the rock resembles a breccia; further east, in the Tonopah Mining Company's property and in the Montana the inclusions are smaller and less abundant; and still further east, in the Mizpah Extension, the inclusions become characteristically tiny, and the green matrix makes up nearly the whole of the rock.

*Relation to Veins.*

The West End rhyolite cuts off the important veins of the first period, of which the Mizpah vein is the chief representative (see Figs. 104 and 101). It is however older than the veins of the second period, which consist of abundant but usually lowgrade or barren quartz; although locally considerable ore has been extracted from these later veins.

*Chemical Composition and Classification.*

The West End rhyolite has been intensely altered by solutions high in silica and potash, as in the case of the Mizpah trachyte.

The few analyses given in the accompanying table (p. 731), therefore, show a considerable range of silica content. The most siliceous ones are entirely similar in chemical composition with the most highly altered trachytes, and correspond to an alaskitic magma. These same alaskitic characteristics mark also the analyses of the West End rhyolite samples furthest down in the scale of siliceous content, the lowest (Nos. 1 and 2 in the table on p. 731), being marked by relatively high silica (72–73 per cent.) and potash (4.3–4.9 per cent.) low iron and magnesia, and very low lime and soda. On account of the high alteration of even the least altered of these glassy rocks, and the similarity of composition and nature of alteration to altered forms of the Mizpah trachyte, there is a possibility that the West End formation was also originally a trachytic magma. Internal evidence is extremely scanty, as phenocrysts are tiny and rare. They consist, where found, of feldspar (probably orthoclase almost exclusively), biotite, and occasional quartz. The presence of this occasional quartz alone prevents the assumption that this rock was originally practically identical with the Mizpah trachyte in composition; and leads to the final assumption that the magma had a composition intermediate between trachyte and alaskite; and was closely related to the Mizpah trachyte magma, but was more siliceous.

The expulsion from the deeper regions of this alaskitic magma, it will be observed, was again followed by the expulsion of large volumes of solutions high in silica and potash, and indeed very similar to the solutions which followed the expulsion of the Mizpah trachyte; and from these solutions the veins and ores of the Second Period were formed.

### THE MIDWAY ANDESITE (LATER ANDESITE).

A large surface area is covered with an andesite which is barren of profitable veins, and which overlies as a later "cap-rock" the Mizpah trachyte, the Montana breccia, the West End rhyolite, and the veins of both the first and second periods. The greater part of this Midway andesite is evidently a flow, which

was poured over a very uneven surface of erosion of the older rocks. The interval between the intrusion of the West End rhyolite and the Midway andesite eruption was considerable—enough, probably, to allow the veins of both the first and second periods to be laid bare at the surface.

The contact of the Midway andesite with the underlying rocks is frequently a fault contact. Where this is not the case, as in certain portions of the West End and Belmont areas, the actual contact with the underlying trachyte is in many places obscure.[7]

In the Tonopah Extension-Sandgrass area, however, basal phases of the Midway andesite, overlying the trachyte, are found, which are unusually fine-grained on account of rapid marginal cooling, and contain inclusions of trachyte, evidently pebbles picked up from the surface over which the andesite flowed. This shows in the 660-level Tonopah Extension and 700-level Sandgrass, but best in the 270-level Tonopah Extension, where it was observed by J. W. Finch, H. W. Stotesbury, and the writer. Here along a flat contact zone several feet thick the andesite contains rounded and subangular (apparently water worn) pebbles of trachyte, up to several inches in diameter. Some of the pebbles contain quartz stringers, which do not pass into the andesite.

In the Montana (765-foot level) there is also a normal basal contact of the Midway andesite with underlying West End rhyolite, this contact being marked, like the other mentioned, by a fine-grained marginal phase, but without inclusions.

### *Alteration.*

The Midway andesite is in many places intensely altered, especially in the vicinity of the chief ore-producing area. Its manner of alteration is, however, usually quite sharply contrasted with that of the Mizpah trachyte which it overlies, a fact that was fully discussed in the original report. The alteration of the Midway andesite has been chiefly to calcite, chlorite, serpentine, quartz, siderite, pyrite, and other secondary minerals, with typically little silicification; hence the rock has assumed (where

[7] Prof. Paper No. 42, U. S. G. S., p. 186.

unoxidized) a characteristic dark, greenish color, and a relatively soft consistency. The alteration of the Mizpah trachyte, on the other hand, has, as stated, been largely to quartz and sericite, with adularia and other secondary minerals; and the altered rock is in many places hard, light-colored, and siliceous. As stated in the original report, the alteration of the Midway andesite is evidently the work of hot ascending waters, and the alteration is indeed the typical "propylitic" alteration so often characteristic of the andesitic wall-rocks of Tertiary bonanza veins like the veins of Tonopah; but at Tonopah this marked propylitic alteration took place long after the formation of the principal veins, and was unaccompanied by any save scattered, and nearly barren veins (veins of the Third Period—to be described later).

## THE TONOPAH RHYOLITE.

### *Distribution and Age.*

The intrusive Tonopah rhyolite-dacite, or Tonopah rhyolite, as it will be called, is described in the writer's published report[8] as occupying an extensive area to the north of the producing part of the district. The southern margin of the exposure of this rock is intricately intrusive into the Midway andesite ("later andesite"); and its northern extent has not been determined.

In this original report the Tonopah rhyolite was described as having a glassy groundmass, often showing flow structure, and frequently showing autobrecciation. "Angular fragments of broken glass, included in a cement of similar glass, and other phenomena, indicate that the lava moved while stiffening." The small porphyritic crystals were determined as orthoclase and andesine-oligoclase feldspars, quartz and biotite.

Lava of similar appearance and composition was described as covering much of the surface in the southern part of the area mapped, and as occurring not only as intrusions but as numerous thin surface flows alternating with pumiceous tuffs. Many of these layers were regarded as probably fragmental, the result of showers of ash and lava fragments during explosive eruptions.

[8] Professional Paper No. 42, U. S. G. S., pp. 41–43.

It was believed that the uniformly intrusive Tonopah rhyolite in the northern area represented the intrusive portions of the same lava which occurred as flows and fragmental layers in the southern area. In both areas the rock in question was provedly younger than the Midway ("later") andesite. In the southern area the beds of this rock overlie a surface formation of rhyolitic (rhyolitic-dacitic) tuffs, flows, and pumice beds, which are themselves younger than the "Midway andesite" and were called the "Fraction breccia."

The bulk of these surface rhyolite-dacite lavas in the southern part of the area were erupted just previous to the formation of a great lake basin, in which were deposited white characteristic tuffs[9] ("Siebert tuffs"). This lake was considered identical with the Miocene Pah-Ute lake of King. It was, however, pointed out that the period of eruption of the Tonopah rhyolite-dacite was a lengthy one, marked by recurring spasmodic eruptions; and that thin sheets of this rock were intercalated with the lower part of the Siebert tuffs. The Siebert lake beds were determined as older than the intrusion of the volcanic necks which form the present hills around Tonopah, which consist of individually distinct but closely related rhyolitic lavas, varying from siliceous rhyolite (Oddie rhyolite) to a dacitic rhyolite (Brougher dacite or rhyolite-dacite). These volcanic necks were also determined as younger than the Tonopah rhyolite-dacite—both the surface formations in the southern half of the area mapped, and the intrusive masses in the northern half of the area.[10] The principal and most conspicuous faulting of the region was shown to have followed the intrusion of these necks. "The faulting was chiefly initiated by the intrusion of the massive dacite necks (the rhyolite necks were probably not so bulky[11]). After this

[9] Tertiary diatoms were found in these tuffs by the writer; and recently Tertiary gasteropods have been found, but as yet have not been studied.

[10] Prof. Paper No. 42, U. S. G. S., pp. 44, 49.

[11] This description was written after the field work of 1903, and the conclusion as to the character of Mount Oddie as a volcanic neck was derived entirely from a study of the Oddie rhyolite surface contacts, which indicated an intrusive volcanic neck broadening or mushrooming upwards. Since that time mine development has shown the shape of this neck, and made an accu-

intrusion and subsequent eruption there was a collapse and a sinking at the vents. As the still liquid lava sank it dragged

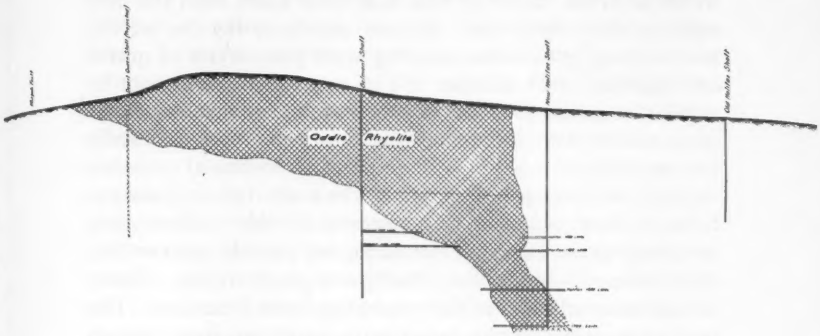



FIG. 102. East-West Section through Halifax and Belmont Shafts. Scale 900 feet to the inch, showing Oddie Rhyolite Neck.

downward the adjacent blocks of the intruded rock, accentuating the faults and causing the described phenomena of down faulting in the vicinity of the dacite."[12] This faulting affected in a striking way the Siebert tuffs, and the surface flows and fragmental beds of Tonopah rhyolite-dacite in the southern part of the area mapped.

### *Origin and Characteristics of "Lower Rhyolite."*

Where this rock is developed in the Tonopah Mining Company's ground, both in the workings and deep drill-holes, study shows that a strip along the contact, irregular and varying in thickness up to say 200 feet, has distinct characteristics from the main mass beneath. This main mass, of which a minimum thickness of 1,000 feet is developed in the Silver Top drill-hole, and of 1,800 feet in the Mizpah drill-hole, and which has been also extensively developed by lateral drilling, is a massive uniform rhyolite breccia with usually no trace of banding, and with uni-

rate section possible. The section, Fig. 102, is based on actual developments in the Belmont and Halifax mines, and was drawn in February, 1915.

[12] Prof. Paper No. 42, U. S. G. S., p. 47.

form characteristics from top to bottom. Close macroscopic and some microscopic study leaves no doubt in the mind of the writer as to the nature of this rock, quite apart from the field relations above mentioned. It is an autoclastic rhyolite breccia, with a glassy groundmass showing small phenocrysts of quartz and relatively fresh feldspar, and often an immense amount of angular inclusions, principally of the same glassy rhyolite, identical in texture with the groundmass, or slightly more or slightly less crystallized, together with frequent inclusions of andesitic rock, of all sizes up to immense blocks many feet in diameter. Some of these inclusions may represent an older andesite, not yet found as an extensive formation, but possibly representing the rock on which the Glassy trachyte originally rested. There are also rare inclusions of shale and of probable limestone. The small phenocrysts of the groundmass sometimes show perfect crystal outlines, but usually they have been broken. The groundmass is typically faintly cryptocrystalline, sometimes faintly spherulitic; in most cases faint wavy flow-lines can be distinguished in it, which curve around the phenocrysts and included fragments. This groundmass invades the quartz phenocrysts in the familiar typical manner of a glassy matrix eating into and resorbing quartz phenocrysts; and these typical invaded quartzes were found in every section examined. This shows that the matrix is uniformly a devitrified glass, and not a "detrital paste." All phenomena indicate clearly a rhyolite glass intrusion, forced upward slowly and spasmodically, with partial stiffening in the intervals between the flow-movements, so that the congealed portions were repeatedly shattered and borne on as inclusions in the still fluid glass, which was itself stiff enough to disrupt in many cases even its own small phenocrysts. Where this autobrecciation is intense, the rock, with its many angular and rounded (corroded) inclusions, and its largely shattered and resorbed phenocrysts, has much the appearance on preliminary examination of a fragmental rock—that is to say, of a detrital tuff formed at the surface.

At and near the upper contact, the character of the rhyolite

is much more variable. The typical rhyolite breccia of the lower portions is also here present, but this is mingled with or alternates with fragments and large masses, up to many feet in diameter, of a dense white rock resembling broken stone-china. Study of the great amount of core from the Silver Top drill-hole indicates that certainly most of this rock is a flow-banded glassy rhyolite, showing sometimes faint but frequently beautiful and delicate flow-structure, and containing usually very sparse but sometimes abundant orthoclase crystals, and occasional quartz crystals, usually unbroken by the groundmass. These white glassy rhyolite layers locally alternate with and pass by transition into fine rhyolite breccia, belonging to and transitional into the more uniform type above described, and these layers have the usual characteristics of glassy groundmass, broken phenocrysts, abundant angular inclusions, and typical quartz phenocrysts invaded by the corroding glassy groundmass; but elsewhere this clean white glassy rhyolite occurs in considerable masses. Careful study of all observed cases of this white banded rock in the upper portion of the "lower rhyolite," including that on the 700[13] Mizpah, has led the writer to the conclusion that all are of the nature described.

In spite of the transitions above noted between the dense white glassy rhyolite and the glassy rhyolite breccia, the latter as a whole is later than the former. Many of the small angular inclusions of the breccia, especially in the upper portion, are of white glassy flow-banded rhyolite evidently belonging to the formation described.

These observations have led the writer to the conclusion that the white banded rocks as a whole represent the first-chilled upper crust of the glassy Tonopah rhyolite intrusion, cooled before the beginning of the process of autobrecciation, which progressed slowly later as the deeper portions of the glassy intrusion moved onward spasmodically, shattering the upper crust.

As regards its contacts with other rocks, the typical "lower

[13] Especially referred to and described by Mr. J. A. Burgess as a probable tuff (ECONOMIC GEOLOGY, Vol. IV., No. 8, p. 687).

rhyolite" breccia (Tonopah rhyolite) is found distinctly and intricately intrusive into the Midway andesite, with a dense flow-banded marginal phase, near the end of the long north cross-cut on the 765-level Montana; and is intrusive as large dikes, in the Belmont, into both the Mizpah trachyte and the Glassy trachyte. In the Mizpah Extension, the Tonopah rhyolite is found intrusive into the Montana breccia.

On account of the relations above described and others the description of which has been omitted, on account of lack of space, the Tonopah rhyolite is believed to represent practically the same magma as the Oddie rhyolite (Fig. 103), and to have much the same relation to this intrusion as has the Montana breccia to the West End rhyolite.

### *Alteration and Relation to Vein-Formation.*

The Tonopah rhyolite-Oddie rhyolite intrusions were followed by the Third Period of vein-formation, which produced usually small but occasionally very large quartz veins, with small amounts of the metals, and, so far as known, commercially valueless. The attendant heated solutions altered the rhyolites considerably and are believed to have been responsible for the more pronounced "propylitic" alteration of the later andesite in many localities, especially near the Tonopah rhyolite contact. Chlorite, epidote, pyrite, magnetite, and probable siderite ("leucoxene") are found as alteration products of the occasional ferromagnesian minerals in the Tonopah rhyolite; and the orthoclase is partly altered to quartz and sericite.

### *Chemical Composition.*

Chemically both the Tonopah rhyolite and the Oddie rhyolite are relatively siliceous rocks—especially the latter—and represent an alaskitic magma. The analysis of the Tonopah rhyolite is often affected by small inclusions of andesite.

## MINERAL VEINS.

### *Veins of the First Period.*

The principal large and rich veins, which have "made" the mining camp of Tonopah, are confined to the Mizpah trachyte, are older than the West End rhyolite intrusions, and all the other known rock formations of the district except the Glassy trachyte.

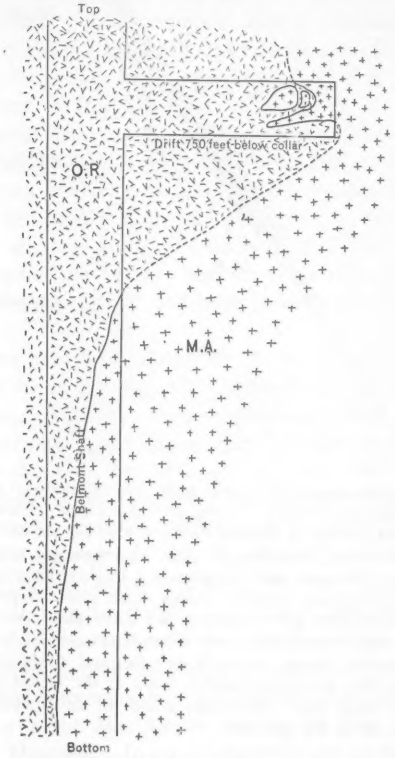



FIG. 103. Vertical section showing intrusive contact of Oddie Rhyolite (O. R.) into Midway Andesite (M. A.), in Belmont shaft, 750–800 feet below collar. Scale, 20 feet = 1 inch. Rhyolite near contact is full of andesite inclusions and very close to contact shows fine flow banding.

These veins have an east to east-northeast strike and usually a northerly dip, at various angles. The ore is typically a fine granular quartz without large quantities of sulphides, very poor in the baser metals and containing silver minerals (and gold) disseminated. The veins have the form of "linked veins," branching and re-

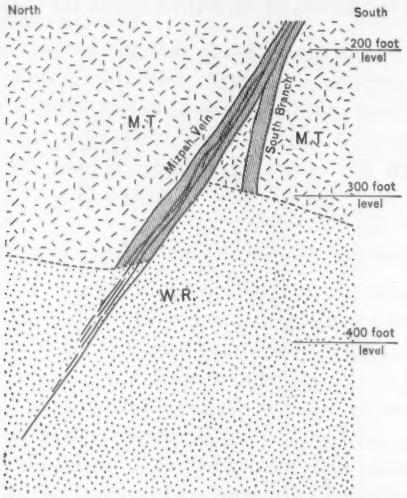



FIG. 104. Vertical cross-section of Mizpah vein, extreme east end of Tonopah Mining Company's property. Scale, 100 feet = 1 inch. Shows the Mizpah veins (of the first period) in Mizpah Trachyte (M. T.) cut off by the intrusive sheet of West End Rhyolite (W. R.). A subsequent normal faulting along the plane of the main vein has given it a trachyte hanging wall and a rhyolite footwall for some distance. Along these fault fractures a certain amount of mineralization and silification has taken place (second period), prolonging the vein, though with only a small fraction of its importance above, down into the rhyolite, where it dwindles and disappears as shown. The veins of the first period are shaded, those of the second period represented by heavy black lines. The south branch of the Mizpah vein is, as shown, cut clean off by the intrusion.

uniting, and the vein channels seem to have been intensely shattered zones rather than large open fissures, so that crustification

is not characteristic, and the veins appear to have originated mainly by replacement of the crushed and sheeted trachyte in the channel-zone.

The primary metallic minerals are silver sulphides, principally polybasite, stephanite, and argentite, with occasional pyrite (less abundant in the veins than in the wall rock), chalcopyrite; galena, and blende. Silver selenide also occurs. Silver chlorides, bromides, and iodides[14] occur, mainly at least as secondary minerals. Gold occurs in the proportion to silver of about 1 : 100 by weight, and is occasionally seen in the free state, which free gold may be in part primary.

The principal veins of this type are the Mizpah, the Valley View, the MacDonald-Brougher, the Tonopah-Extension, and the Belmont, which last may be an extension of the Mizpah vein. These veins are usually large and are nearly all ore, of various grades; the average grade is usually high. They correspond to the best type of the Tertiary bonanza veins of the Pacific petrometallographic province;[15] and have yielded several millions of profit.

These veins have been affected by the various successive rock-strains later in origin than their deposition, and largely later than the intrusion of the various later rocks; these strains have at various periods caused faulting of the veins on both a large and small scale, both transverse to the veins, and along them. The latter form of movement brought about a slipping of one wall on the other and often effected a reopening of the vein-fissure, which opening was subsequently cemented by vein material belonging to one or several of the later stages of vein-formation. It may be stated as a definite rule that the first-period veins do not penetrate the West End rhyolite or any of the other later rocks; and in many cases the veins are abruptly cut off at the rhyolite, sometimes with definite intrusive phenomena, as is the case with the MacDonald vein on the 615 and 765-foot levels of the Montana. In some cases however, at the lower por-

[14] Iodyrite discovered by J. A. Burgess.
[15] Prof. Paper No. 42, U. S. G. S., p. 278.

tion of the original vein, the West End rhyolite forms one wall, a condition which arises from faulting along the vein after its being cut off by the rhyolite (Figs. 104 and 101). This is often characteristic of the Mizpah vein, for example; but where the rhyolite comes in on both sides, the vein becomes very small, or low-grade and barren, or cuts out entirely. The frequent extension of the impoverished vein a little distance into the rhyolite appears to be due to the vein-material of the later periods, which has cemented the post-rhyolite openings, not only along the original vein, but also along the extension of the new fissure downward into the younger rock (Fig. 104).

Occasional blocks of probable Mizpah trachyte and (more frequently) Glassy trachyte, included in the West End rhyolite near its margin, contain quartz veinlets which do not extend into the rhyolite, and so belong to the first period. Several of these cases occur in the Mizpah mine (600-foot level, 600 intermediate, etc.).

The trachyte wall-rocks of the veins of the first period are highly altered, principally to quartz and sericite.

### *Veins of the Second Period.*

The veins of the second period are younger than the West End rhyolite and older than the Midway andesite. They comprise a group of definite sequence whose members have distinct characteristics. The volume of quartz of veins of this period is great, as was pointed out in the original report;[16] indeed, in the aggregate it is probably much greater than that of the quartz of the veins of the first period; but the commercial value of the former is insignificant as compared with that of the latter.

### *Second Period "A" Veins.*

The most conspicuous veins of this second period are large veins of a rather characteristic frosty lustered quartz, with a predominant northeast trend, and a predominant flat dip usually to the southeast. These followed and occupied fault-fissures

[16] Prof. Paper No. 42, U. S. G. S., pp. 96, 97.

which were subsequent to the West End rhyolite intrusion (since they fault this rock) and which fault the principal veins of the First Period. The later quartz which fills these veins is typically barren, or very low grade. Such later veins occupy the Alpha, Beta and other fault-zones in the Mizpah-Silver Top mine.

Probably belonging to nearly or quite the same age is the great MacNamara vein, which is flat, rolling, and gently dipping and which evidently follows a flat fissure-zone of great importance, lying usually between the Mizpah trachyte and the underlying West End rhyolite, but in part cutting out the West End rhyolite entirely and lying between the Mizpah trachyte and the Glassy trachyte below; elsewhere both the Glassy trachyte and the West End rhyolite are cut out, and the vein follows the contact of Mizpah trachyte and Sandgrass andesite. In still other places it occurs at the contact of Montana breccia and West End rhyolite, or West End rhyolite and Sandgrass andesite. In the West End-MacNamara mines, the vein locally arises from the West End rhyolite-Mizpah trachyte contact, so that it has trachyte in the footwall as in the hanging wall. This large vein is usually low-grade or barren; but in certain places yields ore of considerable amount and value.

At the time of this post-West End rhyolite faulting, the initial movement along the Stone Cabin and Mizpah faults[17] also took place, and the fissures thus formed were occupied by usually large low-grade or barren quartz veins from which, however, a certain amount of ore has been mined. (Stone Cabin-Fault vein and Mizpah-Fault vein.) The Mizpah-Fault vein is developed in the Mizpah, and to a less extent in the Montana and Belmont mines. These veins are associated with frequent barite, and often carry scattered cupriferous pyrite. The silver sulphides which carry theoccasional values have a very spotty distribution. Quartz belonging to this period also has cemented reopenings in veins of the First Period, and forms narrow barren extensions of these veins into the West End rhyolite below their actual terminations (Fig. 104).

[17] See Prof. Paper No. 42, U. S. G. S., Plate XVI.

*Second Period "B" Veins.*

The ores of wolfram (tungsten), hübnerite and scheelite, have been discovered in the Mizpah mine by Mr. J. A. Burgess. They occur in both the Mizpah and Valley View veins, especially where one wall is formed by the West End rhyolite. Several localities afford criteria showing that this ore is closely associated with but distinctly later than the quartz described above as *second* Period *A*. On the 600-foot level Mizpah, near the Beta fault, the hübnerite with its associated quartz cuts cleanly a vein of the Second Period *A* quartz, which is itself a barren prolongation of the Mizpah (First Period) vein at this point. Between the 500 and 600 levels Mizpah (Raise 610) where the Beta fault cuts off and offsets the Mizpah vein, a false extension (post West End rhyolite) of the vein on the other side of the fault consists of the barren Second Period *A* quartz with later wolfram-bearing quartz.

This tungsten occurs in many places and though not in commercial quantity, is not a rarity. Its matrix is a peculiar honeycombed quartz whose cavities frequently contain gypsum. The form of some of these cavities suggests that they have been formed by the dissolution of original calcite. The hübnerite also occurs filling small fissures in older quartz. Barite which is quite characteristic of the Second Period *A* veins, also occurs sometimes in the quartz associated with the hübnerite.

*Second Period "C" Veins.*

After the Valley View Vein (First Period) had been offset by the Alpha fault (which was later cemented by Second Period *A* quartz), resumption of stresses produced the extension of one stump of the Valley View vein past the fault, in line with the old vein. In this new extension the quartz is different from that in the main vein, being more clearly crystalline and vitreous, and marked by an abundance of adularia. This vein, in distinction from the original Valley View vein, has characters indicating that it was largely deposited in an open fissure. It is the same type as the Fraction vein, which is an east-west striking, *south-dipping*

vein, and which was low-grade or barren except in spots, or where subsequent silver sulphides had been deposited along crevices in the original quartz.[18]

Veins and veinlets of this type of mixed crystalline quartz and adularia are common, both in the Mizpah trachyte and in the West End rhyolite. They are typically low-grade or barren. They seem to represent the chief period of adularia formation, which was therefore subsequent to the main period of ore-deposition (First Period). Quantitatively, these veins are not of the first importance.

The exact age relations of the Second Period *B* veins to those of the Second Period *C* are not determined, but both are later than the Second Period *A*, and the relations of the Second Period *A* and *B* quartz are very close, suggesting that the *B* immediately followed the *A*, and therefore that the *C* succeeded *B*. The *C* type appears probably older than the *D* type to be described.

*Second Period "D" veins.*

These are east-west veins filling fissures of usually small size in the earlier andesite or the West End rhyolite. They have frequently a south dip. They are marked by a frequent banded or crustified structure, by bands of black sulphides, and by rhodochrosite. The primary sulphides comprise stephanite and polybasite, as is the case in the veins of the First Period. The sulphides of the baser metals are still conspicuous, but chalcopyrite, galena, and blende are more frequently met with. These veins are frequently high-grade, and are responsible for practically all the ore formed since the intrusion of the West End rhyolite. Veinlets of this type have intruded the false (Second Period *C*) extension of the Valley View vein above referred to, and have created some "stoping ore" out of this part of the vein. Fissures carrying ores of this period have also penetrated the large low-grade West End vein (Second Period *A*) in the West End mine, and have created pay-ore shoots. The ore in the MacNamara mine also appears to be due to a deposition of ores of

[18] Prof. Paper No. 42, pp. 140, 146.

this *D* period along fissure-zones in the barren *A* quartz; and the same is true in the Tonopah Extension. Locally in the last-named mine the Second Period *D* mineralization has enriched the West End rhyolite hanging wall, and neglected the original (Second Period *A*) quartz vein, so that the rhyolite has been stoped as ore, and the footwall of the stope is the hanging wall of the main quartz vein. The origin of the pay-ore in the Mizpah-Fault vein is probably similar. Examples of clean veins of this *D* period are found in the Montana and extend to a certain extent into the Midway, where a number of small but fairly high-grade veins, generally south-dipping, occur in the West End rhyolite. The relative proportions of gold and silver values appear to be about the same as in the ores of the "First Period."

The "Second Period *D*" stage represents the second main period of ore-deposition, and althought insignificant as compared with the First Period has furnished considerable pay-ore.

The waters which formed the veins of the Second Period altered the wall-rocks, including the West End rhyolite, intensely, principally to quartz, sericite, adularia and pyrite, with some chlorite and calcite.

*Veins of the Third Period.*

The veins of the Second Period do not occur in the Midway andesite nor the Tonopah rhyolite.

The veins of the Third Period are usually small, sometimes very large. They occur both in the Midway andesite and in the Tonopah rhyolite. So far as observed, they are chiefly associated with the intrusive contact of the Tonopah rhyolite, and their formation seems to have followed the intrusion of this rock.

One of the most striking veins of this class occurs on the 900-foot level Mizpah, in the uppermost portion of the Tonopah rhyolite sheet, and contains a large amount of colorless, usually translucent quartz, with occasionally sulphides in considerable amount. This is a nearly flat vein, approximately parallel to the near-by contact. The content in precious metals is trifling, and the sulphides consist of galena, blende, pyrite, and chalcopyrite.

An assay of a picked sample of sulphide-bearing quartz, taken by the writer, gave, gold, trace; silver, 2.30 oz.; copper, 0.98 per cent.; zinc, 5.82 per cent.; lead, 5.98 per cent. A similar and very likely the same large flat vein was cut in the upper portion of the Silver Top drill-hole, here lying in the Sandgrass andesite somewhat over a hundred feet above the flat Tonopah rhyolite contact.

In the Desert Queen shaft of the Belmont a similar and very likely the same large flat quartz vein was encountered at a depth of 934 feet, in the uppermost portion of the Tonopah rhyolite[19] within 12 feet of the contact. This vein showed a little pyrite and galena, but the highest of several assays showed only 0.08 ounce gold and 2.12 ounces silver with traces of arsenic and copper. This large vein of the Third Period near or close to the upper Tonopah rhyolite contact may be conveniently designated the Desert vein.

In the Mizpah Extension shaft, according to the writer's original published report,[20] the Tonopah rhyolite ("lower rhyolite") comes in at a depth of 430 feet, and continues to a depth of 505 feet, where andesite comes in to a depth of 620 feet, below which the shaft is in Tonopah rhyolite to the bottom (about 1,000 feet). On all three of these Tonopah rhyolite contacts (probably all intrusive), either at the contact or within a few feet of it and usually in the Tonopah rhyolite, large quartz veins occur, containing a notably large amount of pyrite, and showing low assays in gold and silver.

Along the margin of the outcropping intricately intrusive Tonopah rhyolite mass, there is much alteration of the intruded Midway andesite, which is pyritized and contains many quartz stringers carrying pyrite, and locally showing assays in gold and silver, the gold usually predominant.

Except near the margin of the Tonopah rhyolite intrusion

[19] Prof. Paper No. 42, U. S. G. S., p. 193. The enclosing rock of this vein was determined at the time of this published report as Oddie rhyolite; it is now found to be part of the main mass of Tonopah rhyolite and to represent a phase practically indistinguishable from the Oddie rhyolite.

[20] Prof. Paper 42, p. 195.

there has been very little vein-formation either in the Tonopah rhyolite or the Midway ("later") andesite. Occasional small veins in the Midway andesite, away from the contact, consist usually of clear translucent quartz, with frequent calcite. They are invariably nearly barren. Occasionally, as in the Umatilla, these veins are of fair size. Certain broad lode-zones in the Midway andesite show intense alteration and pyritization, with low-grade quartz stringers. The strongest of these Third Period lodes noted (on the Red Plume claim and other claims in the vicinity) form a conspicuous zone on the weathered surface, sharply demarked from the andesite wall-rock on both sides; in width they have been found to vary from 50 to 150 feet, and have been traced without interruption for over 1,500 feet. A more or less pronounced slight rose or amethyst tinge seems to be often characteristic of veins of this Third Period, whether they are encountered in the Midway andesite or Tonopah rhyolite, or in the older rocks, or cementing reopenings of veins of the earlier periods.

The "propylitic" alteration of the Midway andesite (to chlorite, calcite, pyrite, etc.), being most marked near the Tonopah rhyolite intrusions, is probably due to the waters attendant upon or following the Third Period of vein-formation.

### CONDITIONS OF THREE PERIODS OF VEIN-DEPOSITION.

All the evidence tends to show that the zone occupied by the present veins was probably never very deeply buried, and hence that all the veins described were formed at relatively shallow depths. While considerable of the thickness of the original Mizpah trachyte flow has doubtless been removed by erosion, yet it is probable that at the time of formation of the veins of the First Period there was no formation overlying the trachyte, and hence that the depth at which these veins were formed can be easily estimated in hundreds of feet, without having recourse to the thousands. At the time of the formation of the veins of the Second Period, the surface should have been still lower, on account of intervening erosion, and because no known surface

accumulation intervened; but as the central point of deposition of the veins of the Second Period is a few hundred feet lower than that of those of the First Period, the depth at the time of deposition was perhaps roughly the same for the two periods. Between the time of the deposition of the veins of the Second Period, and those of the Third Period, there were very considerable surface accumulations of volcanic rocks (the Fraction breccia, the surface forms of rhyolitic rocks, probably the Siebert tuffs); but there was also great erosion. As the central locus of deposition of the largest known veins of the Third Period is typically a few hundred feet lower than those of the Second Period, these large Third Period veins may have been formed at slightly greater depths than the first two periods; but it is probable that 2,000 feet is a fair guess-estimate.

With this preliminary consideration it is interesting to consider the origin of the various metallic depositions which succeeded one another in this district, and now occupy practically the same zone, overlapping one upon the other.

In a published paper[21] some years ago, the writer advanced the theory that the solutions forming the principal ore-deposits were differentiation products of igneous magmas, and that different metal-groups might be deposited at different temperatures from solutions having a single source and originally similar. Since the terrestrial temperature normally increases with depth, the different metal groups are in the simplest combination of circumstances deposited in successive vertical zones, one below the other. A preliminary division of the vein groups into six was made, which was later increased to seven.[22] They are stated in the order in which under the simplest circumstances they are deposited, from the bottom up, beginning with those formed under the highest temperatures and ending with those deposited at low temperatures, near the surface: (1) the pegmatite zone, containing tin, molybdenum, tungsten, etc., with characteristic gangue

[21] "A Theory of Ore-Deposition," ECONOMIC GEOLOGY, Vol. II., No. 8, Dec., 1907, pp. 781–795.

[22] "Study of a Contact Metamorphic Deposit," ECONOMIC GEOLOGY, VII., No. 5, p. 489.

minerals; (2) the free gold-auriferous pyrite zone, with coarse quartz gangue; (3) the cupriferous pyrite zone; (4) the zone of argentiferous and auriferous pyrite, and auriferous arsenopyrite; (5) the galena-blende zone; (6) the zone of silver and also much gold, associated with antimony, bismuth, arsenic, tellurium and selenium: characterized by tellurides and selenides of silver, gold tellurides, argentiferous tetrahedrite and tennantite, polybasite, stephanite, and argentite; (7) the zone of earthy gangues, barren of valuable metals.

It was pointed out in these papers that on account of changes of temperature in a certain rock zone, metallic depositions belonging to different groups might successively be deposited within the same zone, or even successively occupy a single periodically reopened vein-fissure, the simplest case being due to a gradual fall of temperature due to the downward progress of cooling of an igneous mass; in which case any of the above-defined groups of metals might be superimposed upon one of the earlier-mentioned groups. In a paper on "Ore-Deposition at Aspen, Colorado"[23] it was found that certain vein-groups corresponding to the above divisions succeeded one another, but in the reverse of the normal order named; and this was interpreted as due to a gradually rising temperature (instead of falling) during ore-deposition, due to the attendant gradual upward progress of an igneous intrusion. The consideration was also brought out in this paper that relatively long-sustained temperatures at the critical point for precipitation of a certain mineral-group were necessary for the accumulation of an important representation of this group; while on the contrary, critical temperatures that were rapidly passed resulted in slight or unrecognizable representation of the corresponding mineral-group precipitations, within a certain rock-zone; and the dependence of the relative transitoriness of these temperatures upon the quantity and behavior of intrusive igneous rocks was pointed out.

At Tonopah the veins of the First Period are typically zone No. 6, as above defined; as are also the veins of the Second

[23] ECONOMIC GEOLOGY, June, 1909, Vol. IV., pp. 301–320.

Period *D*. The vein group is the normal one for the shallow depth, Tertiary age, and associated fine-textured or glassy volcanic rocks; and the two classes of veins therefore represent recurrences of the most normal stage of vein-deposition, separated by a sharply intervening period of time. The First Period was, however, long sustained, and resulted in exceptionally large and important veins; the Second Period *D* was sustained for a much shorter time, with correspondingly less important results.

The First Period seems to have followed, with no intervening vein-phenomena, the eruption of the Mizpah trachyte; the Second Period *D* was subsequent to the Montana breccia-West End rhyolite intrusion, but was preceded, subsequent to this intrusion, by distinctly different vein-phenomena—Second Period *A*, *B*, and *C*, whose formation probably represents considerable time. Omitting for the present the *A* and *C* veins, which contain very little metallic mineral (although these are not wanting) and which are therefore not so clearly significant, the Second Period *B* veins contain, in proportion to their limited quantitative amount, abundant minerals of tungsten. This metal is one of the characteristic ones of zone No. 1, as defined above; and in most of the localities where it is known to the writer, it occurs under conditions indicating a relatively high temperature at the time of deposition. This seems to indicate a high though only briefly-sustained temperature following the Montana breccia-West End rhyolite intrusions, and preceding the lower more normal temperature of formation of the No. 6 zone. The gangue minerals of the Second Period *B* veins, however (quartz, some barite, originally probably calcite), are not indicative of so high a temperature as are the tungsten minerals.

The veins of the Third Period, which followed the intrusion of the Tonopah rhyolite, contain very little sulphides, though locally these are bunched and are almost massive. They consist of galena, blende, pyrite, and chalcopyrite; and represent therefore the characteristic association of the lower part of zone No. 5, as defined by the writer. This may also be taken to indicate an abnormally high, though only briefly sustained temperature, following the Tonopah rhyolite intrusion.

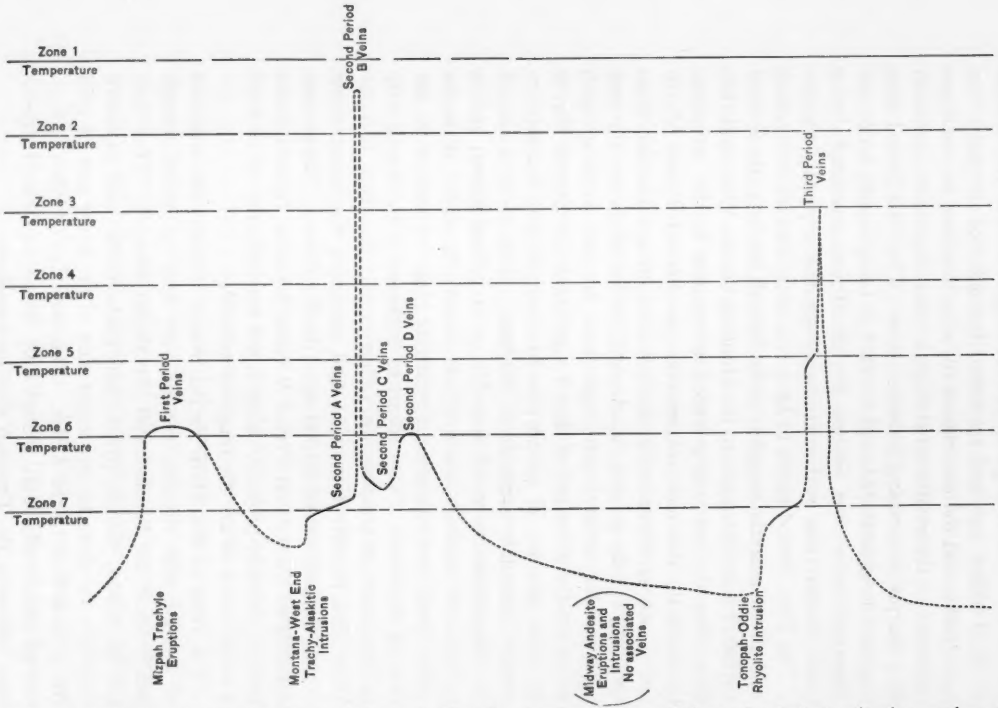



FIG. 105. Diagram of ore deposition at Tonopah, Nevada, showing known relations of principal volcanic eruptions to periods of vein formation; also the hypothetical temperature relations. The dotted part of the irregular line is a temperature curve; the solid parts represent periods of vein deposition.

The succession of apparently distinct vein groups is then: 6–(1)–6–5. The intervening groups are not represented, which may be taken to indicate changes of temperature so rapid as not to leave any record in vein-deposition.

As we lack definite knowledge of the critical temperatures of these zones, and the relative lapse of time between intrusions, the conditions as reasoned out and inferred can be shown only roughly in the diagram opposite, in which the dotted line is a temperature curve and the heavy solid lines represent vein-depositions (Fig. 105). Regarding the temperature of the Second Period *B* veins, however, the character of the gangue material makes it questionable whether this temperature was above that usually normal to zone 3. It is probable that tungsten may be present in a gaseous vehicle in the pegmatitic magmas where it is apparently concentrated, and that when sudden and deep fissuring reaches its habitat, it may ascend rapidly for a long distance into cooler rocks, leaving the pegmatitic solution behind.

The underground temperature of the rocks of the district is still abnormally high, as pointed out by the writer in his published report,[24] where it was suggested that neighboring hot waters, not yet tapped, might be the source of the heat. Later waters having a temperature up to 106–108° F. were encountered in the deep drill-hole at the bottom of the Mizpah shaft and elsewhere.

Summarizing the history of eruption and vein-formation, it may be stated that a trachytic eruption (Mizpah trachyte) was followed by a trachy-alaskitic eruption (Montana breccia and West End rhyolite), and this by an alaskitic eruption (Tonopah and Oddie rhyolites) and that each eruption was followed by a period of active quartz-vein formation. Between the trachytic and the trachy-alaskitic eruptions a typical andesite was erupted (Sandgrass andesite); and between the trachy-alaskitic and the alaskitic periods another typical andesite (Midway andesite) was erupted; and neither was followed by a period of vein-formation. The vein-forming magmatic residues, therefore, seem to have been closely associated with the alkali-siliceous magmas.

[24] Prof. Paper No. 42, U. S. G. S., p. 65.

FIG. 105. Diagram of ore deposition at Tonopah, Nevada, showing known relations of principal volcanic eruptions to periods of vein formation; also the hypothetical temperature relations. The dotted part of the irregular line is a temperature curve; the solid parts represent periods of vein deposition.

FAULTS.

The history of faulting is revealed by this examination to be a complex one. After the eruption of the "Mizpah trachyte," with its "Glassy trachyte" basal phase, the vein channels were formed by the development of a series of east-west, typically north-dipping fracture zones which may have been accompanied by slight faulting.

Nearly or quite at the same time as the development of the east-west fractures, a series of less-pronounced northeast transverse-fractures were formed. These transverse-fractures were present before the initial vein-deposition, which followed the east-west fracture-channels; for they have acted as cross-walls[25] to these earliest veins. Sometimes these cross-planes have no displacement of the vein; again, they are marked by faulting of varying, usually slight, degree. The effect as cross-walls is independent of the degree of displacement, and the slight faulting is probably of subsequent origin, belonging to one of the later stages of movement. At the time of the first (and most important) vein-deposition (veins of the First Period) the direction of pressure in the rocks was evidently such (east-and-west) that the east-west channels were left open, the northerly-striking transverse fissures were jammed shut; hence there was little or no ore-deposition along the transverse fractures, in spite of the important rôle which they played.

Subsequent to the first vein-deposition, it is probable that the first of the important long series of nearly horizontal fault-movements took place, producing a considerable differential movement following approximately the upper limit of the "Glassy trachyte." Along this horizontal zone of disruption and movement the Sandgrass andesite, and later the Montana breccia was intruded. Subsequently this movement was renewed, splitting the Montana breccia intrusion, and along the channel thus formed the West End rhyolite was intruded. A continuation of the movement after the West End rhyolite intrusion produced the powerful gently-inclined fissure which was afterwards occupied

[25] Prof. Paper No. 42, U. S. G. S., pp. 85, 119.

by the West End-MacNamara vein. Other strong flat or flatly-dipping fissures were formed at the same time, some of which faulted the veins of the First Period (as the Mizpah and Valley View veins); and these are exemplified by the Alpha and Beta faults of the Mizpah mine. At the same period, some little movement took place along the earlier northeast (transverse) fractures, such as the Valley View fault, and, further east, a fracture of this system began to assume the proportions of an important fault (Stone Cabin fault), striking northerly, and dipping at a moderate angle to the east. The important Belmont fault developed at the same time. At the same time the veins of the First Period were affected by differential fault-movements, parallel to the walls, and one wall of the vein was typically dropped relative to the other, so that at the contact of the Mizpah trachyte veins with the West End rhyolite below, the rhyolite was frequently slid up along the extended fault so as to form for a limited vertical distance one of the walls of the vein (Fig. 104 and 101).

All of the openings thus formed were cemented by the quartz of the Second Period *A*, which indeed registers the age of this fault-movement.

Later than this, successive fault movements, probably all very slight, produced the typically east-west and often south-dipping fissures which were successively occupied by the veins of the Second Period *B*, *C*, and *D*. Those movements reopened some of the old east-west vein-channels, and cut across the north and northeast veins (of the Second Period *A*) transversely; but though not unimportant in their results as affording channels for vein-formation, they were unimportant from a dynamic standpoint.

These movements took place before the advent of either the Midway andesite or the Tonopah rhyolite.

The study of the Mizpah and Stone Cabin faults especially shows the progressive growth of faulting from the period mentioned down to a comparatively recent one. The older faults belonging to these broad zones of movement are more silicified

by circulating hot waters, the younger ones, which are often found to displace the older ones, less and less so.

The intrusion of the Tonopah rhyolite, as above remarked, appears to have been followed by the development of a strong horizontal fault, later cemented by vein-material of the Third Period; and many faults, including renewed movement along older faults, evidently took place at this time. Such later faults are often marked by considerable silicification, but the quartz, even where abundant, is low grade or barren.

Some of the fault-movements of the Mizpah, Stone Cabin and Belmont fault-zones evidently belong to this period.

Finally a number of very strong faults are entirely unsilicified, and are marked by soft gouge; these are later than the latest stage of silicification. Such is the principal movement along the Mizpah fault, and a large share of the movement along the Stone Cabin, Belmont, and other older faults. At this stage, faults like the Montana fault and the Burro fault originated; and altogether the period was one of intense movement.

In the writer's original published report, it was shown that this conspicuous late fissuring and faulting followed the intrusion of the latest rhyolitic-dacitic lavas, which were largely in the form of volcanic pipes or necks; and that the disturbance was due to the collapse and sagging of the crust around the volcanic necks, which sagged after their intrusion and solidification.[26] This is in accord with the later investigation.

Similarly, it is possible that the periods of fissuring, and faulting which followed the earlier successive intrusions may have been due to the sagging of these lavas on solidification. Such for example is possibly the explanation of the form and distribution of the West End-MacNamara vein, which arches up as an incomplete dome near the contact of or above a similar domical uplift of West End rhyolite beneath which the intrusion, elsewhere a sheet of limited thickness, becomes of unknown depth, a thickness of at least 500 feet having been demonstrated.

The large flat-lying Desert vein of the Third Period, described

[26] Prof. Paper No. 42, U. S. G. S., pp. 47, 68, 80.

above as following at or near the upper contact of the Tonopah rhyolite intrusion, may occupy a fissure of similar origin.

Like considerations may explain the present order of superposition of the successive intrusive sills,—the Sandgrass andesite, the Montana breccia, and the West End rhyolite. The Sandgrass andesite was the first of these, and the subsequent Montana breccia intrusion followed a fissure lying in general at the upper contact of the andesite. Later the West End rhyolite intrusion followed a fissure lying in general at the upper contact of the breccia. The hypothesis of the formation of these fissures above each intruded mass by contraction and sagging on solidification, would explain the locus of successive intrusions.

# DISCUSSION

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

## *NOTE UPON THE OCCURRENCE OF MERCURY IN COBALT ORES.*

*Sir:*—Cobalt has been for a long time the subject of much geological investigation and speculation. Many thousand tons of ore have been shipped from its mines to various reduction plants in Canada, the United States and Europe for treatment by various metallurgical processes. As mercury occurs in combination with metallic silver and other closely allied silver minerals, presumably as an amalgam, in a number of widely separated localities in Europe and North and South America, it is surprising that it was not discovered in Cobalt ores until the writer accidentally detected its presence in the fall of 1910 while developing the Nipissing process for treating the high grade silver ores of the district.

Miller's[1] paper upon the Cobalt Area, published in September, 1911, contains the first published record of the occurrence of mercury in this district. He states that it was discovered by the staff of the Nipissing Mining Company, but inadvertently fails to give the writer individual credit for the discovery. As a matter of fact it was only after a considerable number of determinations had been made upon the ore and "metallics" from several mines, and they had actually seen the mercury, that I was able to convince

[1] Willet G. Miller, "Notes on the Cobalt Area," *Engineering and Mining Journal*, Vol. 92, p. 647.

the regular Nipissing staff that mercury did occur in Cobalt ores.

During the development of the Nipissing Amalgamation Process, the writer had frequent occasion to determine mercury in the tailing in order to establish the mercury loss occurring during amalgamation. The large number of interfering elements which were present in the ore made it necessary to check the method of estimation rather carefully. This was done by taking a California siliceous mercury ore of moderate grade, in which the mercury had been very carefully determined, as a standard. Varying proportions of the original Nipissing ore before amalgamation were mixed with the standard ore and the mercury determined in the mixtures by the method of estimation which it was proposed using upon the tailing. Based upon the assumption that Nipissing ore did not contain mercury, the ore mixtures gave results which were invariably too high. This was clearly due to some interfering element or the presence of mercury in Nipissing ore. Determinations were then made directly upon the Nipissing ore, and the gold beads used in making the determination assumed a white metallic coating which appeared to be mercury. The first determinations were made upon rather low grade ore and, consequently, the amount of mercury involved was very small; it was, therefore, not possible to positively identify the mercury by the appearance of the gold beads. Accordingly the coating was dissolved in nitric acid and subjected to various qualitative tests, which definitely proved it to be mercury. Later, when tests were made upon the metallic silver and dyscrasite, which contained a much larger proportion of mercury, it was at once evident without further confirmation that the coating upon the gold beads was mercury. After the completion of the Nipissing refinery the first charge refined under the direction of the writer in the new reverberatory furnace was a lot of silver nuggets directly from the sampling works. At the end of this operation sufficient mercury was recovered from the flue chamber, which had never been used before, to convince the most skeptical that mercury occurred in Cobalt ores. Below are given a number of determinations of mercury which were made some time ago upon Cobalt ores and metallics.

| Mine. | Material. | Per Cent. Mercury. |
|---|---|---|
| Nipissing | Ore from Kendall vein | 0.26 |
| Nipissing | Ore from veins 63 and 64 | 0.24 |
| Nipissing | Ore from veins 63 and 80 | 0.23 |
| Nipissing | Ore from veins 54 and 64 | 0.24 |
| Nipissing | Ore from vein 64 | 0.37 |
| Nipissing | Ore from vein 61 | 0.41 |
| Nipissing | Ore from vein 12 | 0.62 |
| Nipissing | Concentrates from low grade Kendall ore | 0.11 |
| Nipissing | Tetrahedrite | 0.22 |
| Nipissing | Nuggets from veins 26 and 66 | 2.32 |
| Nipissing | Nuggets, general sample | 2.52 |
| Nipissing | Nugget | 1.12 |
| Nipissing | Surface nugget | 1.12 |
| Nipissing | Nuggets from a mixed lot | 3.54 |
| Nipissing | Nugget from vein 64 | 2.70 |
| Nipissing | Weekly sample of nuggets, vein 64 | 2.56 |
| Nipissing | Weekly sample of nuggets, Fourth of July vein | 4.74 |
| Nipissing | Weekly sample of nuggets, Kendall vein | 4.37 |
| Nipissing | Metallics from second class ore | 1.12 |
| Nipissing | Metallics from second class ore | 1.40 |
| Nipissing | Leaf silver | 1.04 |
| Nipissing | Several samples of low grade ore | trace. |
| La Rose | Nugget | 1.34 |
| Coniagas | Nugget from jigs | 1.48 |
| Chambers-Ferland | Leaf silver | 0.80 |
| O'Brien | Tetrahedrite | 0.50 |
| O'Brien | Tetrahedrite | 0.58 |

Knowing that tetrahedrite occurred in Cobalt ores it was at first assumed that it might be the mercurial variety (schwatzite) and, therefore, the source of the mercury. However, upon making further determinations, it was found that the mercury occurred entirely in the metallics which were chiefly metallic silver and dyscrasite and that the percentage of mercury in the tetrahedrite was a function of the amount of silver in these forms which it contained. (In fact, this is also true of all the ore.) Thus the sample of tetrahedrite from the Nipissing mine contained about the same percentage of mercury as the first four samples of ore noted. These five samples all contained approximately 2,000 ounces of silver per ton. Two samples of tetrahedrite from the O'Brien mine, containing approximately 4,000 ounces of silver

per ton, were found to have slightly more than double the percentage of mercury indicated in the Nipissing sample. It was also thought possible that the serpentine might be the source of the mercury, but this theory was disproved, at least as regards the Nipissing ores, by the fact that, while it was possible for the low grade ores to contain many times the proportion of serpentine that could occur in the high grade ores, yet in no case was more than a trace of mercury found in low grade ores assaying from 10 to 40 ounces of silver per ton. The metallics from the low grade and second class ore contain mercury, but the proportion in the low grade ore is so small that only a trace is indicated when mercury is determined in the whole ore.

In general, the purer forms of leaf silver contain a lower percentage of mercury than the more impure nuggets containing a greater percentage of antimony. Individual masses of the metallics show considerable variation in the percentage of mercury, but ore mixtures as treated in the mill show a far more regular content.

The evidence available seems to justify the conclusion that mercury occurs as an amalgam rather irregularly distributed in the metallic portion of Cobalt ores, with a tendency for the dyscrasite to carry a higher percentage of mercury than the purer forms of silver.

I am indebted to Mr. James Denny and Mr. Joseph T. Mandy for making certain of the mercury determinations cited in this article.

G. H. CLEVENGER.

# REVIEWS

**Third Appendix to the Sixth Edition of Dana's System of Mineralogy.** By WILLIAM E. FORD. John Wiley and Sons, Inc., New York. xiii + 87 pages. Price $1.50 net.

The third appendix, patterned after the two earlier ones, covers the six years from 1909 to 1914 inclusive. An average of eleven pages to a year was given in the first two appendices; this last appendix requires an average of fourteen pages to a year—a healthy increase for the Science. It is interesting to note that in all three appendices only about one-third of the proposed new names are accepted as definitely new species. If only the creators of new mineral names would take this to heart!

The present appendix follows closely the general style of the earlier ones. No attempt is made to list all new crystal forms for established species, although references are given to the articles in which these are recorded. A bibliography of the more important papers on the use of the X-Ray for the study of the molecular structure of crystals is added to the regular bibliography which contains the titles of all important volumes published between 1909 and 1915. Although it is inevitable that in a compilation of new mineral names some omissions will be found, the third appendix seems to cover the field fairly well, and the typographical errors are not nearly so prominent as they were in the second appendix.

Almost needless to say, the third appendix is indispensable to whoever in any way wants to keep in touch with the progress of mineralogy.

W. T. SCHALLER.

# SCIENTIFIC NOTES AND NEWS[1]

THE EIGHTEENTH ANNUAL MEETING of the Canadian Mining Institute will be held in Ottawa, on March 1, 2, and 3, 1916.

A CONFERENCE of geologists engaged in the petroleum industry met at Tulsa, Okla., on January 7 and 8, to discuss problems concerning oil work.

C. MASON FARNHAM has been appointed geologist and examining engineer for the Cerro de Pasco Mining Co.

DR. WILLIS T. LEE, of the U. S. Geological Survey, is giving a course of ten lectures at the Johns Hopkins University on "Mesozoic Physiography of the Southern Rocky Mountains."

THE NINTH ANNUAL MEETING of the Illinois Academy of Science was held at the University of Illinois on February 18 and 19, 1916.

A MEETING was held in the Bureau of Mines, Washington, on January 15, to consider a permanent memorial to the late Dr. Joseph A. Holmes, the founder of the United States Bureau of Mines. A permanent organization for this purpose will be effected on March 4.

PROFESSOR ANDREW C. LAWSON, of the University of California, and Dr. F. W. Clarke, of the U. S. Geological Survey, have been appointed members of the Assay Commission for the coming year.

MR. R. M. RAYMOND, managing director of the El Oro Company, has been appointed professor of mining in the School of Mines of Columbia University, succeeding Professor Henry S. Munroe, who retired last June after twenty-seven years of service.

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice.